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VAPOR BARRIERS IN RESIDENTIAL CONSTRUCTION: WHEN, WHERE, AND IF TO UTILIZE THEM

Project and Report
prepared by
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in partial fulfill of the requirements for completion of
Master of Science in Architecture, Construction Management Option
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Proposal

The major problem cited by independent residential builders in new housing construction is moisture related, primarily, rot, decay, and the growth of molds and fungus. First recognized and investigated in a 1923 Forest Products Laboratory survey of dwellings, condensation and moisture related problems were witnessed in early exterior structure paint failure (U.S. Forest Service, 1949). Current building codes and property standards contribute to the problem since the methods employed are prescriptive rather than performance oriented, and the code requirements have tried to create a universal approach for construction rather than looking holistically at the wall assembly components (Trechsel, Achenbach, and Launey, 1982 and Sherwood and Moody, 1989). The purpose of the proposed project and report will be three fold: 1.) Conduct a review of the current building codes for residential construction practices (CABO, International Residential Code and American Society of Testing and Materials) and provide a discussion of the code prescribed installation methodologies and the information/guidance that should be included; 2.) Produce a guide of best practices for proper design and detailing of vapor barriers according to the primary climatic region conditions for several common wall assemblies utilized in residential construction; and 3.) Analyze common wall assemblies and the associated dew point locations under several climatic conditions utilizing WUFI, a diffusion modeling software program that helps predict/compute relative humidity levels which when used in conjunction with the temperature enables the user to determine the dew point.

Abstract

The major problem cited by independent residential builders in new housing construction is moisture related, primarily, rot, decay, and the growth of molds and fungus. Current building codes and property standards methods are prescriptive rather than performance oriented. Wall assembly components should be considered holistically rather than individually (Trechsel, Achenbach, and Launey, 1982 and Sherwood and Moody, 1989).

The report defines and discusses the physical characteristics and standards of vapor barriers as provided by the American Society of Testing Materials (ASTM) for the design of building systems. The Council of American Building Officials, CABO: One and Two Family Dwelling Code, 1995 Edition, Fourth Printing, and International Code Council, International Residential Code: For One and Two Family Dwellings, codes will then be summarized, discussed, and evaluated to determine whether the code recommendations follow the information from the reviewed literature that has been published with respect to this subject. A recommended description of how to design the wall systems with respect to vapor barriers is provided. WUFI, Wärme-und Feuchteransport Instationär (Transient Heat and Moisture Transport), a computer wall-modeling program, was utilized to determine whether the proposed solutions remain valid once the wall sections were subjected to weather conditions.

The primary conclusion that can be drawn from this report is that the concern when designing, detailing, and constructing a structure for vapor/moisture is that air moves far more vapor and moisture than is diffused through the wall cavity materials. Air movement is the movement mechanism that needs to be addressed in our structures.

Executive Summary

Abstract

Current building codes and property standards contribute to the moisture problem currently being experienced in many of our residences. The methods being employed in the codes [Council of American Building Officials (CABO) and the International Code Councils (ICC)] are prescriptive rather than performance oriented, and have tried to create a universal approach for construction rather than looking holistically at the individual wall assembly components and specific structure's design (Trechsel, Achenbach, and Launey, 1982 and Sherwood and Moody, 1989). The following paper contains a summary of lessons learned during the course of a review of literature, a summary of the ASTM vapor barrier standards, a detailed examination of the current existing building codes in relation to vapor barriers, and concludes with recommendations that are climate specific with regard to the foundation, walls, and roofing systems most commonly utilized in residential construction today.

Keywords

Vapor barriers/vapor diffusion retarders, building codes, air barriers, moisture, and condensation

Introduction

Condensation and moisture related problems were first recognized and investigated in a 1923 Forest Products Laboratory survey of dwellings with early exterior paint failure on residential houses (U.S. Forest Service, 1949). It has more recently been reported, "with the exception of structural errors, 90% of building construction problems are associated with water" and the harmful effects related to its penetration into our structures (Trechsel, Achenbach, and Launey, 1982). Buildings continue to be a source of health problems because of the accumulation of moisture and the subsequent growth of mold and fungi within our structure's envelope.

Current building codes and property standards contribute to this problem because the methods being employed are prescriptive rather than performance oriented. The codes have tried to create a universal approach for construction rather than looking holistically at the wall assembly components and specific structure's design (Trechsel, Achenbach, and Launey, 1982 and Sherwood and Moody, 1989).

A major assumption that this paper espouses is that air moves far more moisture vapor than diffusion through building materials. Following the assumption that air moves more moisture vapor than diffusion, the subject of air transported moisture vapor remains the greatest enemy of the wall system in our residences. The principle of restricting air-transported moisture has created the need to concentrate on quality control in residential construction. The most effective means to prevent or retard the flow of air through a wall system is to ensure that when the wall is

constructed that the air barrier and all penetrations through the wall (such as vents, inlets, and outlets) are correctly and carefully detailed and installed to minimize the harmful effects of air movement within the wall system.

Moisture dissipation from within a wall is directly related to both air movement and vapor diffusion through the structure's wall assembly materials (Carll, 2000). The rampant use of vapor barriers in residential construction has in many instances created redundant vapor barriers within the wall cavity that may trap moisture and water. Even if the vapor barrier is not redundant, the vapor barrier's placement is oftentimes in the wrong location creating as many problems as redundancy. A vapor barrier's location should be carefully designed and specifically applied in relation to the wall design, climatic conditions, and the wall's directional orientation (North, South, East, or West). In order to more effectively control moisture, designers and builders must look holistically at the indoor and outdoor atmospheric conditions of the building system design to create the appropriate foundation, walls, and roof sections for the building assembly (Carll, 2000). The recommended placement of a vapor barrier should not be universal. When determining whether or not to use a vapor barrier, the specific application should be studied, designed, and incorporated.

It should be noted that the term vapor barrier, as used in this paper, has been referred to as a vapor diffusion retarder, vapor retarder, and vapor diffuser in the surveyed literature. The term used on the job site to describe any of these materials is *vapor barrier*. For simplicity and consistency within this paper and utilizing the language used on the job site, all future references to any of these terms (vapor barriers, vapor diffusion retarders, vapor retarders, and vapor diffusers) will simply be referred to as vapor barriers.

A vapor barrier's performance is measured in *perms*, which is "the passage of one grain of water vapor per hour through one cubic foot of material at a pressure differential of one inch of mercury between the two sides of the material" (Allen, 1990). A vapor barrier is any material that has a permeance of less than or equal to 1 in residential construction, but this number is typically much lower for other types of construction (ASTM, 1999; Lstiburek, 2000). Materials that are intentionally utilized as vapor barriers commonly have a perm rating of .1 or less, even though the definition provides for less stringent permeance characteristics (DoE, 2002). To further prevent any trapping of moisture in the wall cavity, the cold side of the material should have a perm rating at least five times greater than the value at the warm side (DoE, 2002). A vapor barrier is not a waterproofing application; it is a material with a low permeance that aims to slow or retard the movement of vapor through the material to prevent the vapor from reaching the dew point on the next cold surface (Bordenaro, 1991; DoE, 2002; Kubal, 2000; ASTM, 1999; Quiroutte, 1991; DoE,

2002; Straube, 2002; Lstiburek and Carmody, 1991; ICAA, 2002). The vapor barrier should ideally be placed so that it is the next cold surface once the dew point has been reached within the wall cavity. A vapor barrier should be included in the wall system design when the designer is seeking to create a moisture and infiltration tight environment for the wall system (Stein and Reynolds, 1992; Lstiburek, 2000). The correct incorporation of a vapor barrier in the wall system can be looked at as a means of helping control condensation in wall assemblies.

The function of an air barrier is to stop outside air from infiltrating the building system materials through the walls, windows, or roof and to keep inside air from exfiltrating through the building envelope to the outside (Quiroutte, 1991). An air barrier may be utilized at any location within the wall assembly and must be specifically designed, detailed, constructed and in order to ensure that it is effective (Rousseau, 1990). Since air leakage is the most significant mechanism to be considered in moisture control, air leakage should be controlled regardless of climate. It should be remembered that air leakage moves far more moisture than vapor diffusion does through materials (Sherwood and Moody, 1989 and Letter, 2000). A key principle to be remembered with an air barrier is that they should be used everywhere, and they should be properly designed and subsequently constructed (Straube, 2002). The air and vapor barrier information in Table 1 is a source for definitions and a list of sample materials.

Air that leaks into a wall assembly must also have a means to exit the assembly. In most cases, air leakage can be corrected through careful detailing and maintaining quality control at the inlet and outlet opening sources of air leakage into wall assemblies (Lstiburek and Carmody, 1991). Inlet openings are typically unsealed electrical outlet boxes, bottom edges of interior gypsum board cladding, or openings/gaps/joints in interior air barrier systems. Outlet openings are joints between sheets of exterior sheathings, top plate and bottom plate connections to the exterior sheathings, service penetrations, and other construction flaws. These openings must be detailed and constructed correctly if the air barrier's integrity is to be maintained.

Table 1 – Vapor Barriers vs. Air Barriers, Definitions and Sample Materials

	Definition	Sample Materials
VDR/Vapor barrier	1. "The control of water vapor diffusion to reduce the occurrence or intensity of condensation" (Straube, 2001) that is driven by diffusion, and 2. May have imperfections and small cracks in its surface without greatly impairing the performance of the permeable vapor barrier (Straube, 2001), or 3. Defined by building codes as anything with a permeability of 1 perm or less (Lstiburek, 2000)	- Polyethylene sheet membrane (Visquene) or film (varying thicknesses, 2-6 mil and in 3-20 foot rolls) sealed with manufacturer recommended caulk, sealants, and tapes - EPDM - Plastic sheeting - Rubber membranes - Glass - Aluminum foil - Sheet metal - Oil-based paint - Bitumen or wax impregnated kraft paper - Wall coverings and adhesives - Foil-faced insulating and non-insulating sheathings - Vapor retarder latex paint - 2 coats of acrylic latex paint top coating with premium latex primer - 3 coats of latex paint - Scrim (open-weave fabric like fiberglass fabric) - Hot, asphaltic rubberized membranes - Some insulations (elastomeric foam, cellular glass, foil faced isofoam) if sealed - Aluminum or paper faced fiberglass roll insulation - Foil backed wall board - Rigid insulation or foam-board insulation - 1/4 inch Douglas fir plywood with exterior glue - High-performance cross-laminated polyethylene (Information from Lstiburek, 2000; ICAA, 2002; Spence, 1998; Bordenaro, 1991; Maness, 1991; Lotz, 1998; Lstiburek and Carmody, 1991; Forest Products Lab, 1949; DoE, 2002)
Air Barrier/ Pressure Threshold	1. "Control airflow and thereby control convection vapor transport" (Straube, 2001), 2. Controls the moisture that is transported along with this airflow (Straube - vapor, 2002); 3. Helps to increase comfort, reduce energy consumption, help control odor, and help reduce sound transmission (Straube, 2001); and 4. Must be "continuous, durable, stiff (or restrained), strong, and air impermeable (Straube, 2001) 5. The point where the air pressure drop occurs within the cavity (Lstiburek, 2000)	- Unpainted gypsum board (sealed) - House-wrap, if properly sealed and continuous - Continuous building paper (15lb or 30lb felt paper) - Plywood sheathing if joints properly sealed - Foam board insulation - Hot, asphaltic rubberized membranes - Some insulations (elastomeric foam, cellular glass, foil faced isofoam) if sealed (Information from ICAA, 2002; DoE, 2002)

Air leakage through a wall assembly nearly approaches zero in modern construction because of the rampant use of sealers and caulks between any and all the joints and materials (Straube, 2002). While the approach specified by most designers today calls for the use of housewrap as the air barrier, they should be cautioned since this material has been shown in the DOE (2000), Holladay and Vara (2000), McDaniel (2000), Holladay (2000), Cushman (1997), and James (2000) articles to allow air, and subsequently moisture, to pass through once it has been stapled or attached by other means. While all the joints may be taped, as directed by the housewrap manufacturer, tapes and sealants are prone to deterioration over time. The importance has been mentioned since housewrap is a frequently used component that must be considered and designed when dealing with moisture. A full discussion of housewrap will not be discussed in this paper.

Air barriers often act like vapor barriers due to the permeance of the materials used (Straube, 2002). The designer should consider whether or not the air barrier material qualifies as a vapor barrier because utilizing a redundant system will often lead to harmful moisture issues within the wall cavity by trapping vapor and creating an ideal environment for rot, decay, mold, and fungi to flourish in (Roger, 1964). Examples of easily incorporated inadvertent vapor barriers include vinyl wall coverings and multiple coats of paint (i.e., 3 coats of latex paint) that inhibit the wall's capacity to dry (Lstiburek, 2000). The inadvertent use of air barriers that behave like vapor barriers contribute to the problems within our structures.

As a building is renovated and repaired, redundancy and inadvertent vapor barriers are often created. For example, a common manner in which an inadvertent vapor barrier is created in a residence is when the occupants repaint a room. The structure's wall, when constructed, may have a primer coat on the gypsum wallboard and two additional coats of non-vapor retarding latex paint. When the occupants repaint their walls to update their home with two new of coats of latex paint, they have unintentionally created a vapor barrier on the interior side of the wall. The inclusion of this vapor barrier either creates a vapor barrier where none previously existed or has now created a redundant vapor barrier because of one that was intentionally installed during construction. Unintentional vapor barriers are frequently incorporated into buildings and should be avoided when possible. Caution should be taken when renovating or updating residences/structures to prevent redundancy.

The predominate approach to climate zone definition has segregated the United States into climatic zones or areas according to the number of heating degree-days that the specific location experiences throughout the year. The climatic zones used in this paper follow these principles:

- *Heating climate* is defined as an area that has 4000+ heating degree-days (Lstiburek and Carmody, 1991).
- *Mixed climate* is an area that has up to 4000 heating degree-days (Lstiburek and Carmody, 1991).
- *Cooling climate* is defined as an area that has 67°F or higher WB temperatures for 3000+ hours during the warmest 6 consecutive months and/or 73°F or higher WB temp for 1500+ hours during the warmest 6 consecutive months (Lstiburek and Carmody, 1991).

The information in Table 2 lists the approximate locations, but the specifics should be confirmed for each locale prior to any design. Specific climatic information may be gathered from ASHRAE, the National Weather Service Bureau, or other relevant sources.

Table 2, States in the various climatic zones of the United States adapted from the graphical depiction of climatic zones from Lstiburek and Carmody (1991)	
Heating Climate	Maine, New Hampshire, Vermont, New York, Massachusetts, Connecticut, Rhode Island, New Jersey, Pennsylvania, West Virginia, Ohio, Michigan, Indiana, Illinois, Wisconsin, Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, Kansas, Colorado, Wyoming, Montana, Idaho, Utah, Nevada, Washington, Oregon, the northern half of California (roughly from San Francisco north), and Alaska
Mixed Climate	Delaware, Maryland, Virginia, North Carolina, Kentucky, Tennessee, Arkansas, Oklahoma, northern 2/3 of Texas (roughly area north of El Paso, San Antonio, and Beaumont), New Mexico, Arizona, and southern half of California
Cooling Climate	South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, southern 1/3 of Texas, and Hawaii

Summary of Lessons Learned from the Review of Literature

The following points have been adapted from a review of literature:

1. In a cold climate, a vapor barrier should be installed close to the interior (warm) side of the insulation.
2. In a hot, humid, tropical climate a vapor barrier should be placed on exterior (warm) side of the insulation, if one is used.
3. In mild, more temperate climates a vapor barrier may or may not be necessary depending upon the specific wall materials. For example,
    a. The brick veneer and spruce siding wall may have a vapor barrier installed on the exterior side of the insulation. It is recommended that no vapor barrier be included because the vapor diffusion difference is not too different when comparing a vapor barrier wall to the same wall without a vapor barrier. The added expense of a vapor barrier should dictate not including one in this design. The effective incorporation of proper ventilation and clear weep holes within this wall cavity design is necessary because once water penetrates the cavity a means to exit and a means to dry should exist.
    b. The use of a plaster veneer wall should be avoided in this climate. This exterior wall system's components (Durarok® and plywood) behave like a vapor retarder for diffusion through the wall system and as such should be avoided to avoid potential redundancy. However, if this wall system is utilized in this climate proper ventilation and clear weep holes within this wall cavity design is necessary to allow water to exit the cavity or to dry.
4. A vapor barrier should only be used if needed, and the use should be based upon the specific wall system design, climate and orientation (North, South, East, or West) of the structure's location and specific wall design.
5. A vapor barrier in a basement should be implemented in the same manner and location as it was in the above-grade wall system.
6. A vapor barrier performs as a ground cover below the slab-on-grade and in crawl spaces and should always be used. The vapor barrier's inclusion in these locations helps reduce

moisture transport through capillary movement/suction from the soil up and into the structure's materials.

7. The vapor barrier does not have to be airtight, but should be installed with as few imperfections as possible to prevent the flow of air and vapor into the envelope. A rule of thumb when installing vapor barriers is "a vapor barrier that covers 90% of the surface is 90% effective" (JLC Staff, 1993).
8. Common wall cover applications act as vapor barriers (i.e., 3+ coats of non-vapor retarding latex paint and vinyl wall covering wallpaper).
9. The building's wall cavity should <u>not</u> be ventilated in hot, humid (cooling) climates.
10. The building's wall cavity should be ventilated in temperate and cold (heating) climates.
11. An air barrier is needed and should be designed into all structures, regardless of climate.
12. Air moves far more moisture than diffusion through materials.
13. Care should be taken when installing an air barrier because the air barrier is <u>only</u> as functional as the air barrier's material integrity (i.e., be free of cuts, tears, punctures, rips).
14. Ventilation requirements in the attic space or crawl space should not be reduced with the inclusion of a vapor barrier.

WUFI – Student Version, a transient heat and moisture transport computer wall modeling program, was used to model vapor diffusion through several common wall assemblies (WUFI, 2003). The effects of air transported vapor remains the primary factor in determining whether or not to utilize a vapor barrier in the construction of a wall system. The results from the WUFI test runs have been summarized below with the assumption that vapor diffusion through the wall system materials is the only driving force within the wall:

1. A vapor barrier <u>is</u> necessary on the outside of the insulation in cooling climates to combat the effects of vapor diffusion.
2. A vapor barrier <u>is</u> necessary on the inside of the insulation in heating climates to combat the effects of vapor diffusion.
3. A vapor barrier <u>is not</u> necessary in mixed climates to address vapor diffusion through the wall system.

The effect of air movement through building materials remains the primary issue to be addressed in building system design and construction. The air barrier should be installed with no penetrations, cuts, tears, or unsealed openings. The air barrier's integrity is critical if the wall components are to be kept dry and not subjected to the harmful effects associated with moisture penetration due to air movement. The air barrier's integrity should be checked prior to the installation of subsequent building assembly layers. The vapor barrier's integrity, on the other hand, does not have to be as perfect if the air barrier has been installed correctly. If the vapor

barrier only has to combat the effects of vapor diffusion through the materials, rather than the effects of air movement and vapor diffusion, then a vapor barrier with a few minor blemishes will perform its role correctly and efficiently. If the vapor barrier is to fulfill the dual role of vapor and air barrier then the rules for installing an air barrier apply.

The quality assurance (QA) and quality control (QC) processes are critical during the construction of the air barrier and the sub-slab ground cover vapor barrier. These barriers should be installed as imperviously as possible and their integrity should be carefully checked prior to subsequent work being placed on top of their respective surfaces. The effectiveness of the wall system air barriers and the sub-slab ground cover vapor barriers are only as effective as they are continuous (JLC Staff Report, 1993). Any and all penetrations should be patched or sealed. QA/QC procedures during construction of these barriers are vital to the success of the wall assembly in the building as it combats moisture.

The directional orientation that the wall faces plays a significant role in the determination of whether or not to include a vapor barrier within the wall. The directional orientation of south and west facing structure walls will require different design parameters than walls facing north and east. The south and west facing walls face more effects from thermal mass and heat gain due to their particular directional orientation. These walls can be expected to maintain higher temperature readings than those on the north and east facing walls throughout the year and the dew point temperatures, and possibly the dew point location, within the wall may vary significantly compared to the same wall on the east or north face of the structure. The specific dew point locations within the wall system should be calculated for each structure's wall when designing the residences wall systems.

Vapor barrier standards defined by ASTM

The ASTM standards, C755, define the vapor barrier's primary function within the wall system as "to control the movement of diffusing water vapor into or through a permeable insulation system" (ASTM, 1999). The diffused movement of vapor into and through a wall system follows one of two flow patterns, unidirectional or reversible (ASTM, 1999). Vapor pressure difference is the driving factor in determining how vapor barriers are to be used since the greater the pressure differential, the greater the rate of diffusion through the assembly (ASTM, 1999). During the design phase, the expected pressure differences should be realistic, not estimated, when determining the vapor barrier requirements (ASTM, 1999).

ASTM defines unidirectional flow, as having a "water vapor pressure difference [that] is consistently higher on one side of the system than the other" (ASTM, 1999). In cooler climates,

this unidirectional vapor flow should include the design of the vapor barrier on the indoor, warmer, side of the wall insulation.

Reversible flow is defined as having a "vapor pressure [that] may be higher on either side of the system, and it often changes with the seasons" (ASTM, 1999). Design for reversible flow conditions do not greatly influence where in the wall system the vapor barrier should be placed. The assumption made with reversible flow is that drying will occur during the opposite season for which the barrier was placed within the cavity.

If a membrane retarder material is to be used within the cavity, ASTM recommends using a retarder with a lower permeance if a five-foot (1.5 meter) wide roll is used, or using a vapor barrier/retarder with a higher permeance if a 20 foot (6.1 meter) width is installed (ASTM, 1999). The reason for the permeance difference, dependent upon the width of the roll, is due to the air penetration through the materials. The smaller width roll of membrane retarder would require a lower permeance because there would be more laps, joints, and seams than the wider roll and thus more air entrained vapor would potentially be allowed to pass through the openings. Even with proper sealing of the laps, joints, and seams of the smaller width rolls, perfect construction quality should never be relied upon for installation, especially since sealants are prone to breakdown over time and the quality of installation cannot be relied upon to be "as recommended" by the manufacturer (which most design specifications indicate). When designing the cavity, low permeability insulation installed with sealed, vapor tight joints often acts like a vapor barrier within the wall. A redundant vapor barrier system should be avoided, but is often inadvertently constructed into the wall system design when a vapor barrier is purposefully used in conjunction with low permeability insulation.

The ASTM standards also recommend the implementation of an air barrier system within the wall cavity (ASTM, 1999). The potential for condensation should be investigated when designing the placement of the air barrier within the wall system (ASTM, 1999). The recommended placement of the air barrier within the cavity is on the warm side of the insulation and should be installed in a continuous, unbroken manner to prevent the uncontrolled movement of air through the wall system, as previously discussed.

The ASTM has defined two recommended vapor barrier design principles called flow-through design and moisture storage. Flow-through design is supposed to eliminate the possibility of condensation within the insulation and should include the use of a highly permeable insulation within the cavity (ASTM, 1999). The purpose of the high permeability insulation is to allow vapor to flow through the insulation and condense, if the vapor is to condense, on the next lower

permeable surface (ideally the vapor barrier) within the system where the liquid would either be drained or removed through ventilation. The moisture storage principle allows for some moisture accumulation within the system's insulation, but the rate of accumulation is small and low permeability insulation should be used (ASTM, 1999). The design utilizing the moisture storage principle assumes that moisture condensation quantities will not exceed the storage characteristics of the material before the moisture is removed from within the system.

The vapor pressure differentials in summer tend to cause vapor to flow in an inward direction, and as such, a vapor barrier should be used on the outer side of the insulation facing the exterior covering of the structure (ASTM, 1999). The ASTM guidance goes on to state "the vapor retarder should still be located on the side of the insulation facing the interior of the building to control vapor flow under the more severe conditions" (from the warm winter side of the system) (ASTM, 1999). The guidance continues, stating that if an impermeable insulation material is utilized, a separate vapor barrier is not needed at all as long as the "joints (if any) are made impermeable by suitable sealing methods" as recommended by the manufacturer (ASTM, 1999). The wall system must be designed for moisture that penetrates the retarder, moves into the insulation, and finally continues on to the outside through some means of ventilation or forced air movement within the cavity (ASTM, 1999). The ASTM standards provide design solutions/recommendations to effectively handle all climatic conditions encountered in the United States construction process, and they provide designers and builders with a clear understanding of how to correctly utilize these materials in the wall systems.

CABO and ICC Code Summaries

The current residential building codes, as published by the Council of American Building Officials (CABO) and the International Code Councils (ICC), have been investigated with regards to the implementation of vapor barriers for residential one and two family dwellings. The applicable code sections from these references have been tabularized in summary form in Table 3 below.

Table 3, Vapor barrier specific code summaries, adapted from CABO (1995) & ICC (2000)

Section	Code	Title	Discussion
321	CABO	"Moisture Vapor Retarders"	- Required in all frame walls and floors, and ceilings, not ventilated to allow moisture to escape. - Vapor barrier to be used on warm-in-winter side of thermal insulation with two (2) exceptions: 1.) Where moisture or its freezing will not damage the materials. 2.) Hot, humid climates: 67°F+ wet bulb temps for 3000+ hours or 73°F+ wet bulb temp for 1500+ hours during warmest six (6) consecutive months of year.

<table>
<tr><th>Section</th><th>Code</th><th>Title</th><th>Discussion</th></tr>
<tr><td>R322</td><td>ICC</td><td></td><td>- In all framed walls, floors and roofs/ceilings comprising elements of building thermal envelope.
- A vapor barrier shall be installed on warm-in-winter side of insulation with three (3) exceptions:
1.) Where moisture or its freezing will not damage the materials.
2.) Hot, humid climates: 67°F+ wet bulb temps for 3000+ hours or 73°F+ wet bulb temp for 1500+ hours during warmest six (6) consecutive months of year.
3.) Counties listed in ICC Table 1101.2, p.72-80 (summarized in report's table 2).</td></tr>
<tr><td>406</td><td>CABO</td><td rowspan="2">"Foundation Waterproofing and Dampproofing"</td><td rowspan="2">- No discussion other than waterproofing applications and moisture barrier installation</td></tr>
<tr><td>R406</td><td>ICC</td></tr>
<tr><td>409</td><td>CABO</td><td>"Crawl Space"</td><td>- When ground surface is treated with a vapor barrier, ventilation opening requirements may be reduced to 1/1,500 of the under-floor area, or
- Ventilation openings may be omitted when continuously operating mechanical ventilation is provided at a rate of 1.0 cfm for each 50 ft^2 of crawl space and the ground surface covered with a vapor barrier.</td></tr>
<tr><td>R408</td><td>ICC</td><td>"Under-Floor Space"</td><td>- Same two rules/exceptions as CABO, plus
- Ventilation openings not required if ground covered with a vapor barrier, space is supplied with conditioned air, and perimeter walls are insulated.</td></tr>
<tr><td>505</td><td>CABO</td><td rowspan="2">"Concrete Floors (on ground)"</td><td>- Vapor barrier with joints lapped at least six inches (6") shall be placed between slab and base course or prepared subgrade if no base course exists
- Three (3) exceptions:
1.) Detached structures that are to be unheated (i.e., garages).
2.) Flatwork not likely to be enclosed and heated later (i.e., sidewalks, patios).
3.) As approved by building official.</td></tr>
<tr><td>R506</td><td>ICC</td><td>Exact words and requirements described in CABO</td></tr>
<tr><td>806</td><td>CABO</td><td rowspan="2">"Roof Ventilation"</td><td>Net free cross-ventilation area may be reduced to 1 to 300 with installation of vapor barrier (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling.</td></tr>
<tr><td>R806</td><td>ICC</td><td>Exact words and requirements described in CABO</td></tr>
<tr><td colspan="4">It should be noted that both CABO and the ICC state, with identical language, that "the total net free ventilating area shall not be less than 1 to 150 of the area of space ventilated except that the total area is permitted to be reduced to 1 to 300, provided at least 50% and not more than 80% of the required ventilating area is provided by ventilators located in the upper portion of the space to be ventilated at least 3 ft. above the eave or cornice vents with the balance of the required ventilation provided by eave or cornice vents."</td></tr>
<tr><td>907</td><td>CABO</td><td rowspan="2">"Built-up Roofing"</td><td>- Vapor barrier to be installed between deck and insulation where average January temperature is below 45°F, or
- Where excessive moisture conditions anticipated within the building.</td></tr>
<tr><td>R907</td><td>ICC</td><td>- Nothing vapor barrier specific</td></tr>
</table>

The information that is presented in Table 4 has been adapted and condensed from the ICC, Section R322, Table 1101.2, pages 72-80. The exact counties/parishes listed should be referenced when designing or constructing a structure in these states, and an exemption is being sought for moisture vapor barrier inclusion on the warm in winter side of the insulation.

Table 4, Adapted from information from ICC (2000): Section R322, Exception 3

State	Number of counties exempted from warm-in-winter V.R. installation
North Carolina	16 of 100 counties
South Carolina	30 of 46 counties
Georgia	109 of 159 counties
Florida	All counties
Alabama	47 of 67 counties
Mississippi	64 of 82 counties
Louisiana	All parishes
Arkansas	44 of 75 counties
Tennessee	2 of 95 counties
Oklahoma	6 of 78 counties
Texas	139 of 254 counties

The two codes have similar intended audiences (one and two family dwelling designers and builders), and the requirements with regards to vapor barriers are nearly identical in both language and verbiage. Both of the codes dictate to the designer or builder where the vapor barriers will be placed with the exception of the section on concrete floors (on ground) where the provision, "or as approved by building official" is included.

The requirements, as outlined in the codes, are fairly specific with regards of where, when, and how to install vapor barriers within the wall systems. The code requirements do not easily allow proposals for acceptable alternatives by designers and builders who may be implementing alternative approaches to construction.

Detail Specifics for Foundations, Walls, and Roofs

Foundations

The foundation vapor barrier design is straightforward and consistent for heating, cooling, and mixed climates. A vapor barrier should be included in all climates as a ground cover under slab-on-grade and in crawl spaces. The accumulation of moisture through the foundation/support elements (slab, basement, crawl space, etc.) is the primary point of entry into residential construction assemblies (Suprenant, 1994). The incorporation of vapor barriers in the foundation design is only going to be as effective as the drainage mechanisms facilitate. Designing proper drainage includes not only collecting the water, but also effectively moving the water out and away from the structure so that the water does not accumulate and then migrate back up and into the wall system. Two typical design details for the slab-on-grade and a crawl space may be seen in Figures 1 and 2.

The placement of the sub-slab vapor barrier will perform a dual role in the structure's moisture protection. The first role is to break capillary movement of moisture upward and into the structure's assembly (Lstiburek and Carmody, 1991). The role of the sub-slab vapor barrier is to break capillarity, and provide the building with its first preventative measure in dealing with moisture by minimizing the potentially harmful effects within the structure. Special care should be taken to ensure that the vapor barrier's integrity is maintained since it is also fulfilling the role of an air barrier.

The second role of the sub-slab vapor barrier is to help prevent moisture migration through the porous concrete (Suprenant, 1994). The vapor barrier material for this application may include sheet polyethylene, damproofing material, multiple layers of roofing paper, or EPDM sheeting. All joints should be lapped at least six inches, and the vapor barrier material should be as impervious as possible to any breaks, punctures, or other such penetrations (Suprenant, 1994). The role of the vapor barrier in this particular application should be designed and constructed in a similar manner as an air barrier within the wall system.

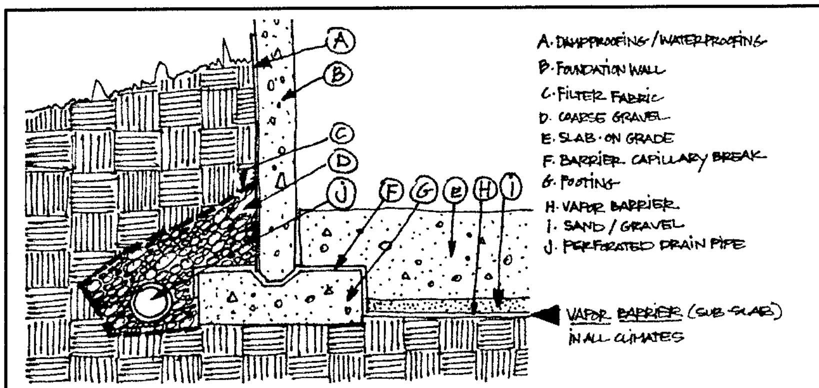

Figure 1, Adapted standard slab-on-grade and basement detail from Ramsey and Sleeper (1992).

The vapor barrier should be placed on top of, and in direct contact with, the compacted subgrade material. Then, on top of the vapor barrier and below the concrete slab, a three-inch thick layer of sand or varied sizes of gravel should be applied and lightly compacted (Suprenant, 1994). Gravel is recommended over sand because gravel is less easily displaced during the placement of the concrete slab and provides a consistently more uniform surface for the slab's placement (Suprenant, 1994). A discussion with a residential house builder stated that this sand or gravel layer is seldom incorporated because of the significant cost and the perceived benefits of incorporation do not outweigh the increased cost of installation (Vinson, 2003). Special care and oversight should be taken during the concrete placement phase since the vapor barrier's effectiveness is proportional to the integrity of the barrier membrane below (JLC Staff, 1993).

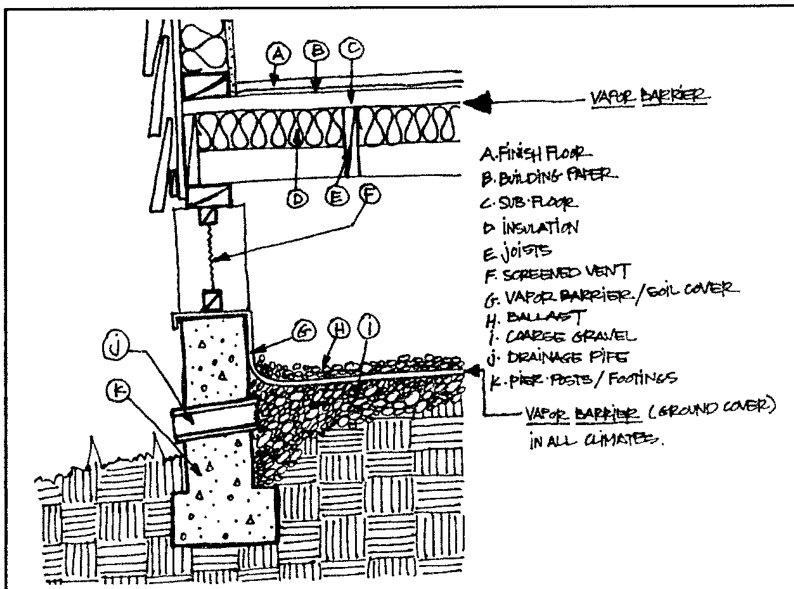

Figure 2, Adapted standard crawl-space detail from FPL (1949) and Ramsey and Sleeper (1992).

The requirements, as outlined in the CABO and ICC codes, make recommendations for the incorporation of vapor barriers in the on-grade, sub-slab section that are in line and follow the recommendations and guidance discovered during a review of literature not presented here.

Walls

The climate where the residence wall is to be located, in conjunction with the composition of the wall components, strictly define how, where, and if a vapor barrier should be included in the design. As previously discussed, the directional orientation of the wall system also plays a significant role in determining when to place a vapor barrier within the wall system. The internal wall temperatures vary significantly depending on if the wall is exposed to climatic conditions on the north, south, east or west sides of the structure. The wall assembly temperatures and thermal mass effects are greatly impacted by the directional orientation. The examples selected do not represent all known housing solutions, merely the most popularly used solutions in the residential construction industry today.

In a heating climate, a vapor barrier should be installed on the warm side of the insulation in both the spruce siding model and the brick veneer models. The type of vapor barrier recommended in this climate is the polyethylene sheet membrane. The use of the plaster-like exterior material, in conjunction with Durarok® and plywood, should be avoided in this climate because of redundancy since a vapor barrier is necessary on the warm side of the insulation in this climate. The plaster wall system's component composition (Durarok® and plywood) on the interior of the plaster coat behaves like a vapor barrier for vapor diffusion through the wall system. It is recommended that this assembly be avoided in mixed and heating climates because of the great potential for vapor barrier redundancy.

In a cooling climate, a vapor barrier should be installed on the exterior side of the insulation. A "Smart Vapor Barrier", or bitumen or wax impregnated kraft paper, is recommended instead of a polyethylene sheet membrane in this climate. It should be noted that clear weep holes and proper ventilation should be utilized if a plaster-like exterior surface is selected.

In a mixed climate, a vapor barrier is not recommended. If a vapor barrier used then it should be installed at the same location within the wall as that for a cooling climate. It should be noted that a vapor barrier is not recommended because of the added cost and high probability of redundancy. If a vapor barrier is used, then install it like in cooling climate structure discussed earlier. The plaster-like exterior wall system, in conjunction with Durarok® and plywood, already behaves like a vapor barrier and a separate vapor barrier should not be installed. However, if this

wall system is utilized in the mixed climate strict adherence to proper ventilation and clear weep holes within this wall cavity design are necessary to allow water to exit the cavity or to dry.

The effects of the redundancy (for example, as caused by multiple layers of latex paint) in a cooling climate's structure are expected to be worse than those in the heating climate. The placement of the intentional vapor barrier on the exterior side of the insulation in a cooling climate and the inclusion of the inadvertent vapor barrier on the interior side of the gypsum board will create a potential vapor trap in the insulation and gypsum board components of the cooling climate's wall assembly. The effect of redundancy caused by paint in the heating climate, with an intentional vapor barrier on the interior warm side of the insulation, creates a vapor trap inside of the gypsum board. It may be concluded that the effects of vapor accumulation will be significantly minimized in the heating climate when compared to the cooling climate's wall.

Proper ventilation and clear weep holes in the wall cavity must exist because once water enters the cavity it should have both a means to exit and a means to dry. If the water is not allowed to exit once it enters the cavity, the water will seek equilibrium within the space and migrate across and through other materials. In this climate, the spruce siding wall assembly has the same recommendations as those for the brick veneer wall. A plaster veneer wall should be avoided in this climate.

Table 5 has been developed as a synopsis or guide for use when making design decisions with regard to the common wall systems in use in residential housing today.

Roofs

The use of a vapor barrier in the roof/ceiling components of the assembly is effective and recommended as a means of being able to reduce the ventilation requirements in this part of the assembly according to the codes. The specifics of utilizing, or not utilizing, a vapor barrier in this area of the assembly is dependent upon the climatic area of the structure, the design of the ceiling/roofing connection, and whether or not the roof is ventilated. All of these items must be considered in conjunction with one another and cannot be looked at or designed in isolation when making a determination for when to utilize a vapor barrier.

A great deal of debate is present in the literature that has been reviewed, and no firm consensus has been reached across all the material reviewed with regards to vapor barriers in the roof system. The only firm conclusion with regards to the inclusion or exclusion of vapor barriers in the roof design is to calculate the specific point where the dew point is reached within the roof system and place the vapor barrier on the next cold surface. The influence of air movement must be considered, as well as the potential for drying through air movement to the interior or exterior

of the roofing system materials. The designer must also be cognizant of the fact that if a vapor barrier is included and the roof develops a leak, the vapor barrier could behave as a vapor trap and cause the system to retain the water by not allowing it to escape. Table 6 has been developed as a synopsis or guide for use when making design decisions with regard to various roofing systems.

Conclusions

In conclusion, builders ridicule the literature and construct out of experience and not what either the literature or wall analysis calculations reveal. The different climate summaries and opinions of the authors are as follows:

1. *Heating Climate*: Vapor barriers should be used in heating climates at all locations within the structure's foundation, wall, and roof assemblies.
2. *Cooling Climate*: The implementation of a vapor barrier should be included within the foundation and wall assemblies of all structures in a cooling climate, but the specific application in the roof remains one area that depends upon the specific, detailed structure design.
3. *Mixed Climate*: A vapor barrier is recommended for the foundation and roof assembly for all structures in the mixed climate, but the when and where to utilize one within the wall system remains less clear and is not recommended. The principles of flow-through design are to be utilized in this climatic area according to the literature reviewed. The flow of air through the wall is the primary driving agent of moisture into and out of the wall assembly depending upon what season the structure is in currently. The principle of flow-through design should be adhered to since it allows wetting during one season and drying during the opposite so that moisture within the cavity attains equilibrium across the wall section during the course of the year.

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Table 5, Wall system synopsis for light-wood frame residential construction

Wall Type (Description abbreviation follows key/diagram at bottom)	***Heating Climate***	***Mixed Climate***	***Cooling Climate***
Wood siding model: (A, B_1, C_1, D, E, F, G, & H)	Incorporate VB_2 between F and G	Vapor barrier not needed	Incorporate VB_1 between E and F
	Recommend using a polyethylene sheet membrane vapor barrier material	If vapor barrier used then place it at VB_1. Not recommended because of the added cost and high probability of redundancy.	Vapor barrier incorporation of a "Smart Vapor Barrier", or bitumen or wax impregnated kraft paper, instead of a polyethylene sheet membrane recommended
	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction	An air barrier should be incorporated, location not critical	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction
Brick veneer model (light wood frame): (A, B_2, C_1, D, E, F, G, & H)	Incorporate VB_2 between F and G	Vapor barrier not needed	Incorporate VB_1 between E and F
	Recommend using a polyethylene sheet membrane vapor barrier material	If vapor barrier used then place it at VB_1. Not recommended because of the added cost and high probability of redundancy.	Vapor barrier incorporation of a "Smart Vapor Barrier", or bitumen or wax impregnated kraft paper, instead of a polyethylene sheet membrane recommended
	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction	An air barrier should be incorporated, location not critical	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction
Plaster-like veneer (may include Dryvit® or EFIS systems) model on light wood frame: (A, B_3, C_2, D, E, F, G, & H)	Avoid this exterior finish system in this climate. Vapor barrier would be located in wrong location due to material properties of C and D.	Exterior wall system (C and D) already behaves like a vapor barrier and this system's use should be avoided in this climate. If used, then construct like in cooling climate.	No vapor barrier needed, since the combination of C and D behave like a vapor barrier.
	However, if this wall system is utilized in this climate proper ventilation and clear weep holes within this wall cavity design is necessary to allow water to exit the cavity or to dry.	An air barrier should be incorporated at the E and F intersection. If this wall system is utilized in this climate proper ventilation and clear weep holes within this wall cavity design is necessary to allow water to exit the cavity or to dry.	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction
Note: All R-values were obtained from Stein and Reynolds (1992), pages 136-143, with the exception Durarok that was obtained from manufacturer's spec.			

<u>Light Wood Frame Construction Wall Section Composition Descriptions, (material thickness and R-value)</u>	
A – *Outside Air* (Not applicable, .17 winter & .25 summer)	E – *Plywood* , Douglas Fir (1/2", 0.62)
B_1 – *Wood Siding* , back-primed (1/2", 0.81)	F – *Insulation* , Unfaced rolled batt (3-1/2", 11)
B_2 – *Brick* , common (2-2/3", 0.2)	G – *Gypsum Board* , primer coat and one latex coat (5/8", 0.56)
B_3 – *Stucco* , plaster/stucco/Dry-vit®/etc (1/2", 0.1)	H – *Inside Air* , air-conditioned (Not applicable,0.68)
C_1 – *Air cavity* (1/2", 1.35)	VB_1 – Cooling climate vapor barrier location and **mixed climate vapor barrier location if used,not recommended**
C_2 – *Durarok®* or similar product (1/2", 0.26)	VB_2 – Heating climate vapor barrier location
D – *Building Paper* , 15#, 30#, permeable housewrap, etc. (Negligible, 0.06)	

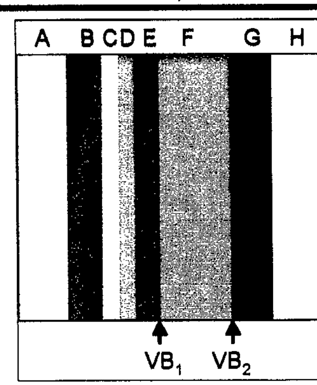

Table 6, Roofing application synopsis

Roof Type	*Heating Climate*	*Mixed Climate*	*Cooling Climate*
Flat Roof	V.B. may be installed between deck and insulation, if design calculations prove its necessity	V.B. should be installed between deck and insulation, if the winter temps are as discussed in codes and design calculations necessitate incorporation	V.B. not needed
Roof with Attic	Super low permeance plastic sheet V.B. & air barrier designed between built-up roofing and insulation in 8000+ heating degree day climates	Higher permeance V.B. & air barrier designed between built-up roofing and insulation	V.B. should not be used in this climate
	Higher permeance V.B. & air barrier designed between built-up roofing and insulation	Circulation/venting must be provided	Air circulation/venting sufficient in hot, dry environments
	Circulation/venting must be provided	Design calculations must be utilized to determine inclusion or exclusion	Air circulation/venting should be avoided due to high moisture concentrations in hot, humid environments
	Design calculations must be utilized to determine inclusion or exclusion		Air barrier designed to prevent air leakage
Cathedral Ceiling	V.B. installed below the insulation (in the interior side of insulation)	V.B. installed below the insulation (in the interior side of insulation)	V.B. not necessary
	Ventilation at the eave and ridge vented	Ventilation at the eave and ridge vented	Ventilation requirements same as attic space and should occur at eave and ridge if ventilated
	Design calculations must be utilized to determine inclusion or exclusion	Design calculations must be utilized to determine inclusion or exclusion	

NOTE: The CABO and ICC codes state, "[n]et free cross-ventilation area may be reduced to 1 to 300 with installation of vapor retarder (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling." The allowed reduction does not appear to make any sense for the climatic areas where roof ventilation is required. One of the purposes of roof ventilation is to allow the space to dry out should the space below the roof become wet. The ventilation reduction allowance under the codes would hamper drying through ventilation. The opinion of the author is that the codes allowed reduction in ventilation within the roof cavity is not recommended. The ventilation of the roof is necessary in effectively combating moisture accumulation in heating and mixed climates but not in cooling climates.

1.0 Literature Review for Vapor Barriers in Residential Construction Applications

1.1 Introduction

The major problem cited by independent residential builders in new housing construction is moisture related, primarily, due to rot, decay, and the growth of molds and fungi. Condensation and moisture related problems were first recognized and investigated in a 1923 Forest Products Laboratory survey of dwellings due to early exterior paint failure on residential houses (U.S. Forest Service, 1949). It has more recently been reported, "with the exception of structural errors, 90% of building construction problems are associated with water" and the harmful effects related to its penetration into our structures (Trechsel, Achenbach, and Launey, 1982). Current building codes and property standards also contribute because the methods being employed are prescriptive rather than performance oriented and these codes have tried to create a universal approach for construction rather than looking holistically at the wall assembly components (Trechsel, Achenbach, and Launey, 1982 and Sherwood and Moody, 1989).

Several assumptions and limitations were been made in the course of the literature review, during the code analysis, and the test data results interpretations. A major assumption that this report espouses is that air moves far more moisture vapor that diffusion through materials. Following the assumption that air moves more moisture vapor than diffusion, the subject of air carried moisture vapor remains the greatest enemy of the wall system in our residences. The principle of preventing air-transported moisture has created the need to concentrate on quality control in residential construction. The most effective means to prevent or retard the flow of air through a wall system is to ensure that when the wall is constructed that the air barrier and any penetrations (such as vents, outlets, etc.) are correctly and carefully detailed and installed to minimize air movement into the wall system. It is the opinion of the author that if careful and thorough attention to these details is done that the effects of moisture vapor penetration in our wall systems will be reduced.

It should be noted that the term vapor barrier has been referred to as a vapor diffusion retarder, vapor retarder, and vapor diffuser in the literature surveyed. For simplicity and consistency within this report, all future references to any of these terms (vapor barriers, vapor diffusion retarders, vapor retarders, and vapor diffusers) will simply be referred to as vapor barriers from this point forward.

The literature review has been broken down into six primary sections for initial investigation and basic understanding of the role that vapor barriers play in dealing with moisture in residential construction. The literature review will: 1.) Provide definitions to be utilized in the course of this investigation, 2.) Explain what moisture is, 3.) Investigate how moisture is generated, 4.) Study some means for dealing with the moisture transport mechanisms, 5.) Perform a comprehensive review of why vapor barriers are used today, and 6.) Conclude with a review of the how to design

and implement vapor barriers in building assemblies (foundations, walls, and roofs/ceilings) according to what has been published.

1.2 Keywords and Definitions

The report has the following keywords: moisture, condensation, vapor barriers/vapor diffusion retarders, and air barriers.

The following definitions will be used when referencing these terms in the discussion that follows in the subsequent sections.

Adsorption	The soaking in of moisture (Kubal, 2000), and The attraction of water vapor molecules close to solid molecules by complementary polar nature of solid molecules or the polarity induced in solid molecules by dispersion and induction effects (Straube, 1988)
Absorption	The collection or condensation of moisture on the surface of a material (Kubal, 2000)
Air Barrier	Any material that blocks the flow of air through a building system, or the point where the air pressure drop occurs within the cavity
Air Infiltration/Transport	Movement of air through a wall system from an area of high pressure to an area of low pressure, this is typically a fast process (Krogstad and Weber, 1999) and (Lstiburek, 2000)
Condensation	The moisture contained within air that is deposited in a liquid or solid state on a cool surface (Krogstad and Weber, 1999)
Dew Point (DP)	100% relative humidity, or the point when dew will form and water vapor will condense when saturated air touches the first surface that is at or below the air's dew point temperature (Stein and Reynolds, 1992), or "the temperature at which a specific atmosphere is saturated with water vapor" (ASTM, 1999), or the temperature at which a volume of air will become saturated, and below which condensation will occur (Krogstad and Weber, 1999)
Desorption	"The action or process of releasing an absorbed substance from something" (Guralnik, 1982)
Dilution Ventilation	Similar process to dehumidification (Lstiburek, 2000)
Dry-Bulb Temperature (DB)	"Temperature of ambient mixture of air and water vapor measured in the normal way with a simple thermometer" (Stein and Reynolds, 1992)
Enthalpy	"The sum of the sensible and latent heat content of an air-moisture mixture, relative to the sensible plus latent heat in air at 0°F at standard atmospheric pressure" (Stein and Reynolds, 1992)
Evaporation	"A process in which something is changed from a liquid to a vapor without its temperature reaching the boiling point" (Guralnik, 1982)
Humidity Ratio	"The amount of moisture by weight within a given weight of air" (Stein and Reynolds, 1992)
Perm	The unit of measure used to measure the passage of one grain of water vapor per hour through one cubic foot of material at a pressure differential of one inch of mercury between two sides of a material (Allen, 1990)
Relative Humidity (rh)	"Ratio of density of water vapor in air to maximum density of water vapor that such air could contain, at the same temperature, if it were saturated" (Stein and Reynolds, 1992)
Resistance	The degree to which material restricts the flow of water vapor through it (O'Connor and Johnson, 1995)
Saturation Line	The line on the psychrometric chart where the dew point is reached in a specific building system and condensation will occur

Splashback	Water bouncing off the ground and splashing back onto the structure (Fisette, 1995)
Thermal Insulation System	"Thermal resistance to heat flow combined with means for attachment to the surface to be insulated, and with facings, vapor diffusion retarders, joint sealants, or protective coatings as installed." (ASTM, 1999)
Vapor Diffusion	Process by which moisture moves from air with a higher dew point temperature to air with a lower dew point temperature seeking equilibrium, this is typically a slow process (Krogstad and Weber, 1999), or the movement of moisture in the vapor state through a material as a result of vapor pressure difference (from a area of high pressure to and area of low pressure or concentration gradient) and/or temperature difference (warm side of a material to cold side of a material or the thermal gradient) (Lstiburek, 2000)
Vapor Diffusion Retarder (VDR) or Vapor Barrier	"Those materials or systems which adequately retard the transmission of water vapor under specified conditions. (For practical purposes it is assumed that the permeance of an adequate retarder will not exceed 1 perm, although at present this value may be adequate only for residential construction. For certain other types of construction the permeance must be very low.)" (ASTM, 1999), or Any material that has a permeability of 1 perm or less (Lstiburek, 2000)
Water Leakage	The water penetration of a wall system that causes damage (Krogstad and Weber, 1999)
Water Vapor Diffusion	"The process by which water vapor spreads or moves through permeable materials caused by a difference in water vapor pressure." (ASTM, 1999)
Water Vapor Permeability (Permeability)	"The water vapor transmission of a homogeneous material under unit vapor pressure difference between two specific surfaces, per unit thickness." (ASTM, 1999), or "the rate of water vapor transmission induced by a difference in vapor pressure through a certain area of material, per unit of thickness" (Holladay, 2000)
Water Vapor Permeance (Permeance)	"The water vapor transmission of a material under unit vapor pressure difference between two specific surfaces." (ASTM, 1999), or the amount of water vapor diffusing through a material (O'Connor and Johnson, 1995), or "the rate of water vapor transmission induced by a difference in vapor pressure through a certain area of material" (Holladay, 2000)
Water Vapor Transmission	"The steady-state time rate of water vapor diffusion or flow through unit area of a material, normal to specific parallel surfaces under specific conditions of temperature and humidity at each surface. (ASTM, 1999), or "the rate at which a certain weight of water vapor passes through a certain area of a material, under certain test conditions" (Holladay, 2000)
Wet-Bulb Temperature (WB)	"Temperature shown by a thermometer with a wetted bulb rotated rapidly in the air to cause evaporation of its moisture" (Stein and Reynolds, 1992)

1.3 Review of Literature

1.3.1 What is moisture?

Several underlying principles exist when trying to understand building systems and the capacity of the system materials and design to carry, transport, and store water (regardless of its form). The principles can best be summarized with the statement that "water is lazy, and it will always chose the easiest path to travel" (Lstiburek, 2000). The purpose of this literature review will be to gain an understanding of the basic principles of water in its moisture phase and then develop an understanding of how moisture moves through building system materials.

The basic principles of moisture closely adhere to the second law of thermodynamics. The second law deals with the natural flow of energy processes and can be summarized as; things are constantly seeking a state of equilibrium and move from areas of more to areas of less. Applying this principle to vapor pressure, areas of high vapor pressure move towards areas of low vapor pressure and this can be correlated to movement from warm areas to cold areas (Stein and Reynolds, 1992).

Webster's Dictionary has defined moisture as "water or other liquid causing a slight wetness or dampness" (Guralnik, 1982). Moisture is all around us. Its presence is created with each activity we perform, and it is in each material we use in the course of our daily lives.

- It is present as a vapor in the air all around us (ASHRAE, 1972).
- It is adsorbed in the materials we use (ASHRAE, 1972).
- It can change forms from a vapor to a liquid to a solid depending upon the temperature, pressure, and relative humidity levels (ASHRAE, 1972).
- It desires as a vapor "to move from high concentrations to low concentrations, or from more to less" (Straube - moisture, 2002).

Moisture can be transported through four movement mechanisms: 1.) Liquid flow, 2.) Moisture transport due to capillary suction, 3.) Air movement, and 4.) Vapor diffusion (Lstiburek and Carmody, 1991 and Straube, 2002). Each of these mechanisms must be dealt with during the design and construction of the structure's systems (foundation, walls, and roof) in order to effectively respond to moisture (Lstiburek and Carmody, 1991). The moisture movement control mechanisms must be specific and not generic with regards to what climatic region of the United States the designer or builder (simply referred to as designer from this point forward) is designing or planning. The design for moisture must be climatically specific since each climatic area of the country dictates different details that are responsive to the different environmental conditions to be experienced.

The predominate approach to climate zone definition appears to have segregated the United States into climatic zones or areas according to the number of heating degree-days that the specific location experiences throughout the year. Thus, each designer should analyze his or her particular code and climate to determine how to address this subject. The climatic zones adapted as the most common follow these principles:

- *Heating climate* is defined as an area that has 4000+ heating degree-days (Lstiburek and Carmody, 1991).
- *Mixed climate* is an area that has up to 4000 heating degree-days (Lstiburek and Carmody, 1991).

- *Cooling climate* is defined as an area that has 67°F or higher WB temperatures for 3000+ hours during the warmest 6 consecutive months and/or 73°F or higher WB temp for 1500+ hours during the warmest 6 consecutive months (Lstiburek and Carmody, 1991).

The specific locale's climatic information may be gathered and computed from ASHRAE, the National Weather Service Bureau, or other relevant sources. Lstiburek and Carmody have defined these areas using a map of the United States. The information in Table 1.1 lists the approximate locations, but the specifics should be confirmed for each locale prior to any design.

Table 1.1, States in the various climatic zones of the United States adapted from the graphical depiction of climatic zones from Lstiburek and Carmody (1991)

Heating Climate	Maine, New Hampshire, Vermont, New York, Massachusetts, Connecticut, Rhode Island, New Jersey, Pennsylvania, West Virginia, Ohio, Michigan, Indiana, Illinois, Wisconsin, Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, Kansas, Colorado, Wyoming, Montana, Idaho, Utah, Nevada, Washington, Oregon, the northern half of California (roughly from San Francisco north), and Alaska
Mixed Climate	Delaware, Maryland, Virginia, North Carolina, Kentucky, Tennessee, Arkansas, Oklahoma, northern 2/3 of Texas (roughly area north of El Paso, San Antonio, and Beaumont), New Mexico, Arizona, and southern half of California
Cooling Climate	South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, southern 1/3 of Texas, and Hawaii

1.3.2 How is moisture generated?

Indoor moisture generation initially comes from numerous construction conditions and sources. After construction has been completed, and the initial high concentrations have been removed, some accumulated construction moisture must still be dealt with in the structure. Source moisture from the daily activities occurring in the structure and multiple external sources, such as rain penetration, are the greatest sources of moisture. Moisture is generated by each and every human, plant, and animal. In addition, many materials, appliances, and processes utilized in our daily lives and activities generate additional moisture. Some examples and the quantities of moisture generated from construction, combustion sources, and daily activities are listed in Table 1.2. While these numbers appear to be high in many instances and have not been confirmed by any known research data, the quantities are very similar when compared to the sources from which the table's data was created. The exact quantities, while seemingly high and questionable to the author, do make the point that each and every activity that we participate in creates moisture in our living spaces that must be dealt with in our structure's assembly.

Table 1.2, Quantities of moisture generated by daily activities adapted from Rogers (1964) and Straube (2002).	
Source	**Moisture Production**
Stone concrete	1 ton/1000S.F. of 4" thick floor slab
Gypsum concrete	2.7 tons of water/1000S.F. of 2" roof slab
Gypsum plaster	1600 lbs. of water/1000S.F. of 1" plaster
Heating salamanders	4.92 liters of water/gallon of oil burned in an unvented space heater
People (evaporation per person)	0.75 (sedate), 1.2 (avg.) to 5 (heavy work) liters/day
Humidifier	2-20+ liters/day
Hot Tub, Whirlpool	2-20+ liters/day
Firewood, per cord	1-3 liters/day
Washing Floors etc.	0.2 liters/day
Dishwashing	0.5 liters/day
Cooking for four	0.9 to 2 (3 with gas range) liters/day
Frost-free refrigerator	0.5 liters/day
Typical bathing/washing per person	0.2 to 0.4 liters/day
Shower (ea.)	0.5 liters/day
Bath (ea.)	0.1+ liters/day
Unvented Gas Appliance	0.15 kg/kWh for Natural gas, 0.1 kg/kWh for Kerosene
Seasonal Desorption (of new materials)	3-8 liters/day depends on the house construction
Plants/ Pets	0.2 – 0.5 (Five plants or one dog) liters/day

While it is impossible to totally eliminate moisture as a source, understanding its movement into our structures must be better understood by designers and correctly detailed in the design documents. Moisture becomes a concern within a structure through the movement mechanisms of liquid flow, moisture transport due to capillary suction, air movement, and vapor diffusion (Lstiburek and Carmody, 1991 and Straube, 2002). The principles of moisture movement regarding each of these topics are critical to understanding the movement of moisture within our wall assemblies.

1.3.2.1 Liquid Flow

Water enters our structures mostly through its flow as a liquid. Water is able to enter the wall system in liquid form in a relatively short period of time due to the design and detailing of the exterior envelope. The detailing of splashback is also critical in the design of wall since this is an area that may allow the base of the wall cavity to pull water back inside and up into the wall cavity through capillary suction (Fisette, 1995). The detail that deals with splashback may not allow drained water to fully move away and exit the wall system structure (Fisette, 1995). Wall design, with respect to liquid flow, can be broken down into three primary methods of construction: mass/storage walls, perfect barriers, and screened-drainage walls (Straube, 2002; ASTM, 1999).

1.3.2.1.1 Mass/Storage Walls

The ideal of the mass/storage wall is a very thick wall section that deals with moisture intrusion through its mass and thickness of construction. Water only tends to penetrate small distances through these types of walls and is not as prone to penetrate completely through the wall due to the girth and width of the wall and the nature of materials typically utilized (concrete, stone, etc.)

(Straube, 2002). Water must search for cracks, voids, and openings as it moves from the exterior skin through the entire cross section and then locate openings, cracks, and voids within the interior sections of the wall for it to migrate from exterior to interior. The path that the water must travel within this wall section must be continuous since the material thickness and the quantities being absorbed tend to stop or inhibit water's entry. These walls are very effective at stopping liquid flow of water, but are nonetheless very expensive, time-consuming, and often difficult to construct in today's construction market (Straube, 2002).

1.3.2.1.2 Perfect Barriers

The perfect barrier type of wall enclosure primarily works well in laboratory and experimental situations, but can rarely if ever be accomplished for long, if at all, in the built environment due to poor field construction quality (Straube, 2002). The perfect barrier wall system is the ideal to be targeted with each construction project. The material must be installed perfectly and then behave exactly as it was designed. The perfect barrier does exactly what its name implies; it provides perfect protection from water intrusion. The perfect barrier stipulates that no openings, crack, or voids exist within the building system. Manufactured homes often strive for this type of construction, and builders and designers attempt to create this type of structure by sealing all the openings and joints during construction (Straube, 2002). This type of construction requires extreme quality control at all phases of construction installation. Sealants, impervious sidings, and other means used in perfect barriers break down over time.

1.3.2.1.3 Screened Drainage Walls

The most common type of enclosure in use today is the screened-drainage wall (Straube, 2002). The screened-drainage wall assumes that water will enter the building system, and then takes steps to mitigate the harmful effects of water entry into a closed cavity by designing a means of removal. The design recommendations drawn by this report will utilize the screened-drainage wall concept since this technique is involved in the residential lightwood frame construction industry.

Once water has entered the wall cavity it can do a number of different things depending upon the conditions it is exposed to. Water can become a solid, liquid, or vapor depending upon the temperature and pressure in its environment. Liquid water may enter the wall cavity through cracks, voids, openings, and then be absorbed by any material it may come into contact with. Wood siding and brick are extremely porous materials that allow a great deal of water to pass through. Once water has penetrated these materials and the exterior skin, the materials on the interior portions of the wall easily absorb and then diffuse this water. If the water that has entered the cavity is absorbed and stored by the materials inside the cavity, the water can then be easily turned from liquid to vapor through processes such as the sun warming the exterior siding on a

warm day. Once this liquid has been converted into vapor, it may pass more easily through the material's pores and any materials that have a higher permeability than the layer where the vapor currently resides. It may then be moved from its current location to other areas in the wall assembly as it seeks a state of equilibrium. It is this movement of water in its vapor state that vapor barriers aim to control. The majority of moisture problems in residential construction are related to liquid water entry, not vapor condensation generation (Holladay, 2000). The elimination of liquid water entry into the wall cavities all but eliminates the moisture issue within the building systems.

1.3.2.2 Capillary Suction

Moisture transport due to capillary suction primarily deals with moisture movement into the building envelope from the exterior and then its redistribution as condensation within the building envelope (Lstiburek and Carmody, 1991). Capillary suction deals with the moisture pressure differentials between materials and the transport of moisture across materials where there is no noticeable break in the material. Typical modes of transport that utilize capillary suction exist where channels or paths exist in materials that can store or move liquid. It is also common for a nonabsorbent material, such as metal, to allow water and moisture to be transported when they are sandwiched together. In the case of a nonabsorbent material used in the wall assembly, water or moisture can be transported due to pressure differentials that exist within the wall system. Typically the migration occurs from areas of high pressure to areas of low pressure and the state of equilibrium is constantly being sought. The vacuum or suction created during this migration subsequently draws the water upward towards other materials along these similar material planes.

1.3.2.3 Air Movement

Air transported moisture is moved from areas of high air pressure to areas of low pressure and closely follows the second law of thermodynamics, stated earlier in Section 1.3.1 (Lstiburek, 2000). An air current is the fastest means of transferring moisture within a building cavity (DoE, 2002). Air currents move "...in the range of several hundred cubic feet of air per minute" and this "...accounts for more than 98% of all water vapor movement in building cavities" (DoE, 2002). It has also been documented that vapor diffusion through a weather resistive barrier would be 2/3 of a pint of water during the heating season while the same material with a 1/2-inch hole through it will produce up to 50 pints of water during the same heating season (DoE, 2000). Air leakage is the most significant mechanism of moisture transfer and should be controlled regardless of climate within a concealed space (Rousseau, 1990; Sherwood and Moody, 1989). The effects of air leakage must be effectively addressed during the design and then be correctly and carefully installed during construction.

Insulation causes water vapor temperatures to drop rapidly which can cause condensation if the relative humidity conditions are correct (DoE, 2002). Moisture, when the state changes from vapor to liquid, is said to have reached its dew point or has reached "the temperature at which a specific atmosphere is saturated with water vapor", or the temperature at which a volume of air will become saturated, and below which condensation will occur (ASTM, 1999 and Krogstad and Weber, 1999). The physics of how moisture contained in air reacts in different temperature conditions has been defined and documented in psychrometric charts. These charts help determine where the dew point will be reached within cavities and when moisture within the air can no longer maintain its gaseous state and becomes liquid condensate (DoE, 2002).

Determining when the dew point will be reached can be accomplished utilizing a psychometric chart. In order to utilize a psychrometric chart, the designer must make some design parameter assumptions about the environmental conditions under which the wall assembly will be utilized. Some of these assumptions include maintaining a constant relative humidity within each material; no airflow through the assembly, the wall is a perfect barrier, etc. The designer must have the indoor and outdoor dry bulb temperature and the indoor and outdoor relative humidity conditions. The design temperatures are not conclusive numbers but are industry accepted approximations used to calculate the dew point within the wall cavity. The process can be further used to determine the exact location in the wall assembly that the dew point will be reached. By utilizing the heat exchange formula obtained from Stein and Reynolds (1992) <u>Mechanical and Electrical Equipment for Buildings: 8th Edition</u>, in conjunction with psychrometric charts it is possible to determine where the dew point will be reached in the assembly. The point where the dew point occurs is where the designer should place design emphasis and address the effects of moisture. The following heat exchange formula helps determine these locations:

$$q = \Sigma(U \bullet A)\,\Delta t$$

where, q is the total heat exchange conducted through the building assembly

U and A are specific to each skin element in the building assembly, and

Δt is the change in temperature difference across the entire building assembly.

The following example shows how the air temperature changes as it move through the building assembly. The wall section used in the Stein and Reynolds (1992) <u>Mechanical and Electrical Equipment for Buildings: 8th Edition</u> example is constructed, moving from the interior to the exterior, of a brick wall, normal 6-inch batt insulation, 1/2-inch plywood, and a 1-inch wood siding (Stein and Reynolds, 1992). Other assumptions that have been made are that the interior air temperature is 68°F and the exterior air temperature is 32°F (see wall section sketch in Figure 1.1), the relative humidity has not changed through the wall cavity, and the wall cavity is a perfect barrier (Stein and Reynolds, 1992). The computed temperatures at each material change have

been diagrammed in Figure 1.1. The temperatures were computed using the formula discussed above and the computational calculations have been shown in Table 1.3.

Table 1.3, Calculated temperature change from one material to another within a wall section copied from Stein and Reynolds (1992), <u>Mechanical and Electrical Equipment for Buildings: 8th Edition</u>

R - value	Component	ΣR-value from interior	Temp Drop from Interior (°F) using (R total at component/ΣR for wall assembly) x Δt	Temp Drop From Outer Edge of Component (°F)
0.68	Inside air layer	0.68	(0.68/21.46) x 36 = 1.1	68 - 1.1 = 66.9
0.20	Common brick	0.88	(0.88/21.46) x 36 = 1.5	68 - 1.5 = 66.5
19.00	Nominal 6-inch insulation	19.88	(19.88/21.46) x 36 = 33.3	68 - 33.3 = 34.7
0.62	1/2-inch plywood	20.5	(20.5/21.46) x 36 = 34.3	68 - 34.3 = 33.7
0.79	1-inch wood siding	21.29	(21.29/21.46) x 36 = 35.7	68 - 35.7 = 32.3
0.17	Outside air layer	21.46	(21.46/21.46) x 36 = 36	68 - 36 = 32

Then using a psychrometric chart and an accurate relative humidity for the project's specific location, the dew point can be determined for the wall assembly by calculating the dew point at each of the various material changes within the wall section utilizing the R-values for each of the materials, an accurate relative humidity level for the area, and accurate design temperature to be experienced. A diagrammatic psychrometric chart with sample numbers is shown in Figure 1.2, and the associated definitions may be referenced from Section 1.2, pages 21 - 22. The dew point location, under the specific relative humidity and temperature conditions, for the specific designed

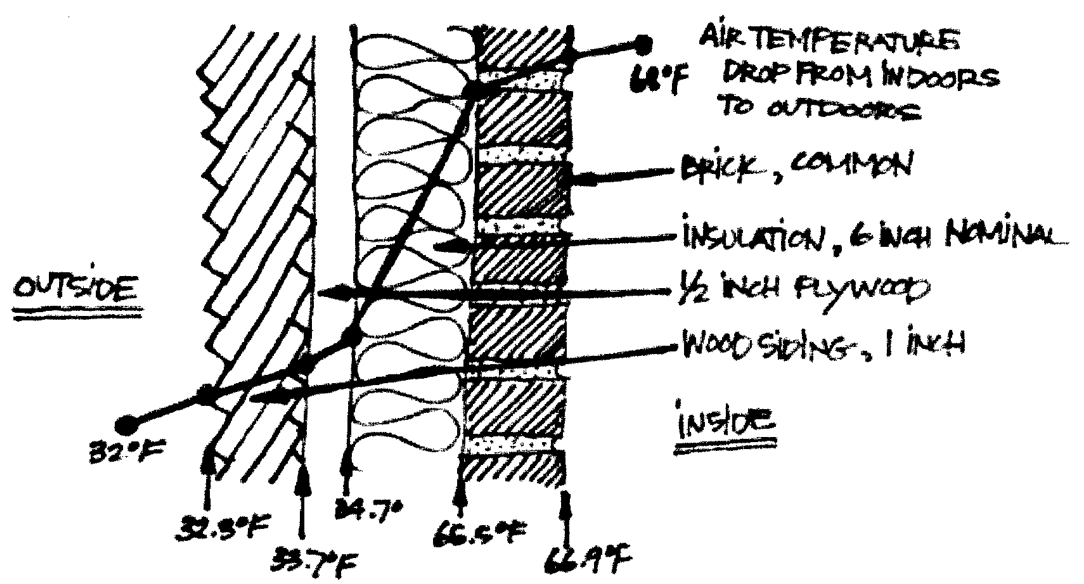

Figure 1.1, Sample wall section with temperature changes diagrammed adapted from Stein and Reynolds (1992), <u>Mechanical and Electrical Equipment for Buildings: 8th Edition</u>

wall assembly will then allow the designer to more easily determine the steps necessary to address vapor condensation within the particular assembly. The dew point for a specific wall section should be calculated using the average historical monthly temperatures and relative

humidity conditions over the course of a year. Once the designer has the dew point locations for the specific wall section, the specific design details may then be designed to respond to moisture within the wall cavity.

The following example explains how to utilize the psychrometric chart in determining where the dew point will be reached under certain design conditions. The sample wall section and calculated temperatures are used from Figure 1.1 and Table 1.3 and the dry bulb temperatures are used for the indoor surface and the intersection of the brick and the insulation, the various dew point temperatures are calculated for the designed wall system by using a psychrometric chart. The dry bulb temperature is 66.5°F at the material change from brick to insulation. This is

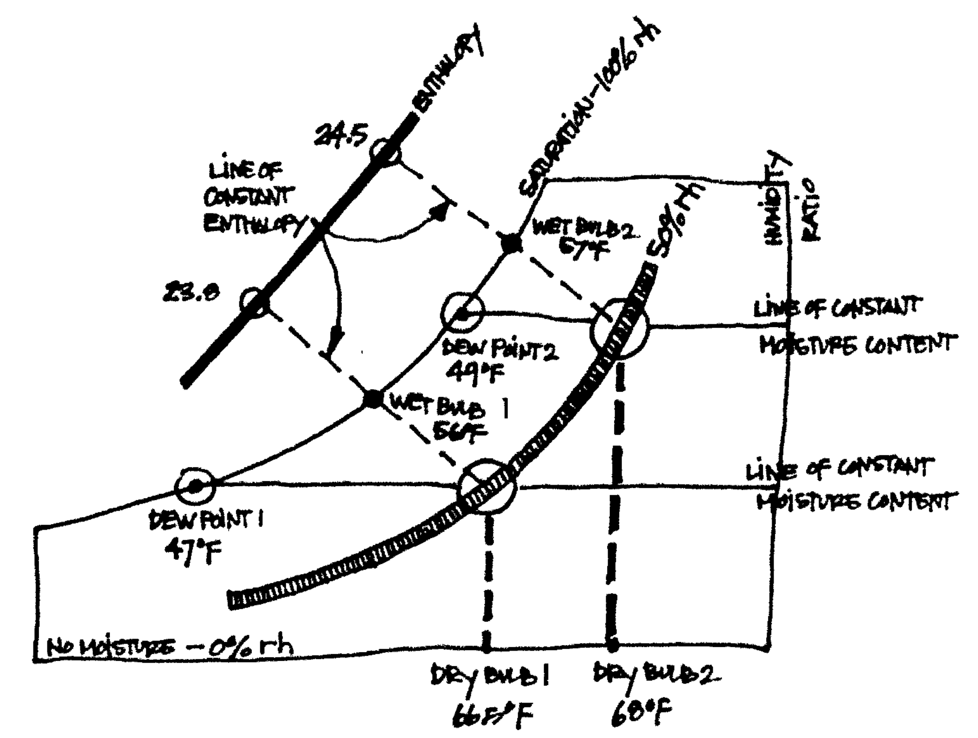

Figure 1.2, Sample psychrometric chart, adapted from Stein and Reynolds (1992), <u>Mechanical and Electrical Equipment for Buildings: 8th Edition</u>

from the calculations in Table 1.3 and this point is shown as Point 1 in Figure 1.2 (psychrometric chart). Following the psychrometric chart lines vertically to the intersection point of the design relative humidity line (assumed in this example to be 50% relative humidity), and then following the line of constant enthalpy over to the 100% relative humidity (saturation line) shows that the dew point for 66.5°F and 50% relative humidity conditions and at this location is 47°F. Following the same assumptions for the indoor dry bulb 2 (inside air layer temperature) temperature of 68°F with 50% relative humidity provides the designer with a 49°F dew point temperature. The same calculations/extrapolations must to be done for all the other surfaces to determine at what temperature condensation will occur within the wall cavity for each of the various materials. It

should be remembered that the relative humidity levels will not remain constant for any climate, but the designer must use the most representative historical numbers in determining how to design the wall cavity section and where (if at all) to utilize a vapor barrier in the design.

1.3.2.4 Vapor Diffusion

Through the process of diffusion, water vapor is transported from areas of higher vapor concentration to areas of lower vapor concentrations and is constantly seeking and desiring a state of equilibrium (Straube, 2002). In order for moisture to be a problem in a constructed structure, four basic conditions must be satisfied:

1. *"A moisture source must be available,*
2. *There must be a route or means for this moisture to travel,*
3. *There must be some driving force to cause moisture movement, and*
4. *The material(s) involved must be susceptible to moisture damage"* (Straube, 2002).

Water vapor can also be described by its drive through a material as being either positive or negative. Positive vapor drive can be described as moisture vapor traveling from moist, warm outside air to the cool, drier interior area (Kubal, 2000). Typically, much of the country experiences positive vapor drive during summer conditions, or simply as vapor's desired movement from the exterior to the interior. Negative vapor drive process describes vapor movement from the warm, moist interior air being pulled outward to the drier, cooler air by the differences in vapor pressure (Kubal, 2000).

Vapor diffusion primarily deals with moisture movement from the exterior and from within conditioned spaces into the building envelope. Diffusion principles are closely related and associated with air movement and controlling/stopping airflow through the building envelope. The "diffusion of moisture through a material is a function of its permeance to vapor and the vapor pressure difference across its surface" and thus by lowering the vapor permeance of the material the diffusion through it will ultimately be lower (Rousseau, 1990). The overall process of water vapor diffusion through a wall system is a very slow process. The movement of moisture in its vapor state is a function of the vapor permeability of a material and the vapor pressure differential that acts across the wall system's material cross section (Lstiburek and Carmody, 1991). Vapor diffusion is a function of the specific climatic area where the structure is located. In cold climates, vapor diffusion will typically move moisture from within the conditioned space into the wall assembly (Lstiburek and Carmody, 1991). In warm, climates, the vapor diffusion process moves moisture from the exterior into the building assembly and then into the conditioned space (Lstiburek and Carmody, 1991). It should be remembered that air leakage and air movement

accounts for far more concentrations of moisture movement than does vapor diffusion (Letter, 2000).

1.3.3 How do you deal with the moisture transport mechanisms?

Once the moisture transport methods are understood, the designer must then address each transport mechanism individually and find a solution for controlling moisture's movement within the structure. In theory, if one of the moisture movement mechanisms, previously discussed could be removed from the scenario then moisture as a concern in the structure could be eliminated entirely (Straube - moisture, 2002). Moisture is all around us, and to fully eliminate any of these items/sources is impossible. However, employing better techniques and paying more attention to the detailing of several critical areas during design and in the subsequent construction of the structures can minimize the harmful effects of moisture within our structures. Placing emphasis on the effects that moisture has on our structures could eliminate many health concerns and eliminate building deterioration due to rot in our residences (Trechsel, Achenbach, and Launey, 1982). A key principle to detailing with moisture in mind is to follow the guidance of "keep it out, and let it out when it gets in" (Lstiburek, 2000). In order to design a solution, the designer must address the principles of capillary suction, liquid flow, evaporation, ventilation, and finally vapor diffusion and air leakage (Straube, 2002). Understanding these principles and concepts is critical in dealing with moisture within a structure and designing a moisture responsive structure.

1.3.3.1 Capillary Suction

The pull of moisture and water into the building is called capillary suction. One way of breaking the capillary suction is the incorporation of an air space within the wall that facilitates drainage and acts as a capillary or surface tension break between the cladding and rest of wall (Straube, 2002). Capillary suction may be created by using similar material surfaces, for example, placing two plates of glass next to one another creates a plane in which water is easily transported often draws up water. The same principle exists between the siding and the wall structure and can be corrected in practical applications by several methods such as: 1.) Painting the siding, 2.) Placing sealant at laps in the siding, 3.) Placing tacks at laps in siding, 4.) Painting the back of siding or back-priming the siding, 5.) Designing an air space between the exterior siding and the nonabsorptive building paper, 6.) Placing siding directly on absorptive building paper, 7.) Leaving an air space behind brick veneer, 8.) Breaking contact with the foundation soil under the slab, 9.) Utilizing an air space between the siding and the nonabsorptive building paper, and many others (Lstiburek and Carmody, 1991). One effective means of breaking capillarity between a footer and the foundation wall is by placing a sheet polyethylene layer or by applying dampproofing on the top surface of the footer prior to placement of the foundation wall as diagrammed in the Figure 1.3 sketch (Lstiburek and Carmody, 1991).

1.3.3.2 Liquid flow

Drainage and liquid flow of water that enters the wall cavity is primarily an issue of utilizing good detail design and then implementing effective quality control during the construction. Resistance of the wall to water intrusion is determined by:

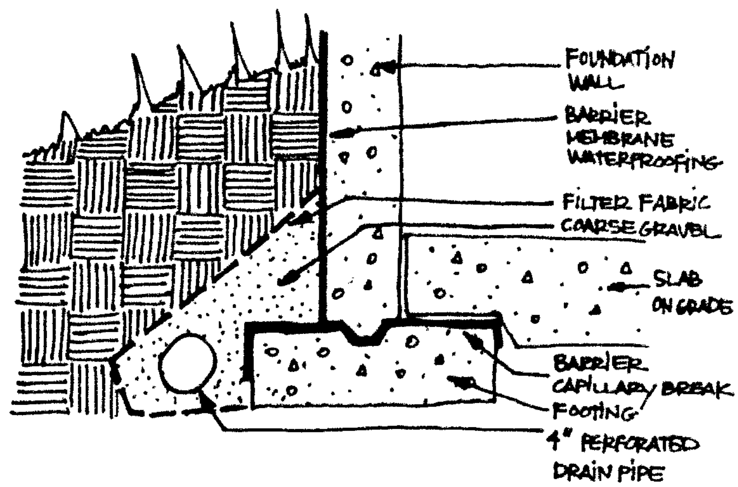

Figure 1.3, Sample footer diagram adapted from Lstiburek and Carmody (1991), <u>Moisture Control Handbook: New, low rise residential construction</u>

- Resistance of the wall to leakage (Carll, 2000),
- Resistance of the materials within the wall to be damaged should they become wet (Carll, 2000), and
- Ability of the wall to rapidly dissipate any intruding water entering the cavity (Carll, 2000)

Leakage can best be dealt with through ventilation applications and allowing any liquid flow of water that may enter the wall cavity to escape through weeps or other intentionally designed drainage points. Liquid flow escaping through weeps and drainage points acknowledge that water will enter the wall cavity and as such must be allowed to escape. To properly handle this liquid entry, proper flashing techniques are the first layer of defense for the structure. Flashing, drip edges, and appropriate sloping must all be correctly designed and then constructed (Straube, 2002). Excellent checklists were developed in Paul Fisette's article, "Making Walls Watertight", which addressed the critical areas of a wall and things to be accomplished during construction. The checklists have been recreated and consolidated in Table 1.4 for reference when performing quality control on a residential construction project's housewrap, corner boards, window flashing, and siding (Fisette, 1995).

Table 1.4 – "Making Walls Watertight" Checklists From Paul Fisette's article, "Making Walls Watertight" from *Journal of Light Construction*, Volume 14, Number 3, December 1995, pages 35-38.
Housewrap Checklist
• "Use housewrap or felt paper on all houses, no matter what kind of siding you are using." • "The wrap should be continuous; avoid patchwork of small pieces." • "Provide an unrestricted path down and out of the space behind the siding. Wall membranes should overlap by 3 inches horizontally and 6 inches vertically. Tape all seams." • "Protect all pathways into the building envelope by lapping housewrap over flashings."
Corner Board Checklist
• "Install felt paper or housewrap at all corners." • "Double-wrap corners by applying vertical felt or housewrap splines under the corner boards." • "Don't caulk the joint between the siding and corner board; caulk deteriorates over time, providing a

pathway for water to get into the frame and preventing trapped water from escaping."
Window Flashing Checklist
• "Protect the top of the window flashing with overlapping wrap." • "Double-overlap housewrap around nailing fins of vinyl and clad windows." • "At sills, splines must direct water over underlying housewrap." • "At head, leave a 1/4 inch gap between the window flashing and bottom edge of siding to prevent wicking of moisture."
Siding Checklist
• "Don't install board siding on a diagonal." • "For horizontal board siding, use top-grade boards with no knots, splits, or other defects. Install T&G and shiplap siding so that the joints between boards drain away from the sheathing." • "For panel siding, use housewrap over studs. Housewrap should overlap Z-flashing at the joint between panel courses." • "Protect wall sheathing close to grade with bituminous membrane." • "Siding should overlap sill-to-foundation joint by at least 2 inches."

Proper drainage is also done through the implementation of weep holes or designing drainage points correctly. Weep holes, when they are utilized, should be kept free of obstruction and the path leading to the weep holes should be clear so that water can travel to and exit through these designated points easily and readily (Lstiburek and Carmody, 1991). The importance of the weep holes and drainage points also facilitates the implementation of ventilation within the structure's wall cavity (Lstiburek and Carmody, 1991). The approaches to weep holes and drainage points should be properly sloped, and elevated correctly so that water cannot flow into the openings from the outside but still exit the wall easily. The area around these openings should also be free of any outside obstructions such as vegetation and soil embankments that could hamper air circulation or drainage. The openings should be clear and visible from the exterior of the structure. Regardless of the wall assembly design, proper drainage must be considered and designed to allow for drainage at the bottom of the wall.

In order to properly deal with leakage and drainage in construction several principles should be remembered:

1. Think like water!
2. "If you can't figure out how to flash it, don't build it." (McDaniel, 2000)
3. Water is easily controlled if you design a path for it to flow, remember typically water flows downhill except under capillary suction conditions.
4. "Water is lazy. Water will always choose the easiest path to travel." (Lstiburek, 2000)
5. Pay attention to how you flash, lap and layer any flashing or housewrap in the flow direction. (McDaniel, 2000)
6. A weather resistive barrier is nothing more than a drainage plane to control the flow of water. (DoE, 2000)
7. Avoid capillary suction by designing effective breaks at suspected junctions that promote this condition.

1.3.3.3 Evaporation

The evaporative process of moisture within the wall cavity is very closely related to the properties associated with ventilating the wall that will be discussed in the next section. However, evaporation may occur from the inside or from the outside (Straube, 2002). Evaporation is tied to the characteristics of the specific, individual material utilized (Straube, 2002). The evaporation process is difficult to separate and closely related to the ventilation properties contained in the designed wall cavity.

1.3.3.4 Ventilation

Ventilation of the wall assembly is a good means of dealing with moisture and leakage and provides a means of drying components should they get wet. Ventilation follows the air pressure differential principle that was discussed earlier and allows rising air heated by the sun to pull air and force air movement within the wall cavity (Straube, 2002). The air pressure differential principle allows for the difference in pressure across the wall section to act as a means of pulling air into the wall cavity while facilitating pressure equalization through the process of convection. Designing an exit, as well as an entry, allows airflow to move through the wall creating convection patterns within the cavity, and cavity condensation may be controlled by facilitating control over where condensation could accumulate (Straube, 2002).

Ventilation should be closely examined and investigated in relation to the climatic area that the structure is being designed for. Ventilating may be detrimental and actually facilitate adverse moisture conditions within the wall cavity in certain climatic areas. As a general rule, the wall cavity design should not be ventilated in a hot, humid climate due to the fact that warm air is capable of maintaining and holding more moisture than cold air. Ventilating in this area could add to the moisture levels within the wall if air were allowed to freely flow through the wall in these areas (Lstiburek and Carmody, 1991). For the other more temperate and cold regions of the country ventilation of the wall cavity should be encouraged. Minimizing holes and penetrations to lower the air volume change within the wall cavity could inadvertently facilitate wetting of the wall cavity materials and reduce the opportunity for drying to occur (Lstiburek, 2000). By not allowing moisture that accumulates within the wall cavity to dry, interior moisture levels rise and condensation could become visible on interior surfaces and windows. The conditions favor mold/mildew growth, and ultimately decay within the wall cavity and attic spaces if the problem goes unnoticed for long (Lstiburek, 2000). The need to dehumidify the space or implement dilution ventilation is necessary to help eliminate these types of problems in the unventilated wall cavity (Lstiburek, 2000). An air space utilized in design should have "a clear space with a minimum thickness of 3/8 of an inch, although 1-2 inches is recommended" (Lstiburek and Carmody, 1991).

1.3.3.5 Vapor diffusion and air leakage

Vapor transport through diffusion and air leakage can best be understood once the difference between an air barrier and a vapor barrier has been explained. In wall assemblies there are two primary barriers that are installed, but they perform drastically different roles in dealing with moisture and vapor penetration within the wall assembly. These two barriers, vapor and air, are typically used or required by code during the construction of a structure. The purpose and use of air and vapor barriers are often confused by the designers, builders, and code officials (Straube, 2001). It should also be remembered that water vapor moves through the processes of vapor diffusion, air transport mechanisms, heat exchange, and the other means previously discussed that deal with water's movement (Lstiburek, 2000). To help simplify and clarify the differences between these two barrier/retarder systems, definitions and sample material lists are provided in Table 1.5 below.

Table 1.5 – Vapor Barriers vs. Air Barriers, Definitions and Sample Materials

	Definition	Sample Materials
VDR/Vapor barrier	"the control of water vapor diffusion to reduce the occurrence or intensity of condensation" (Straube, 2001) that is driven by diffusion, and may have imperfections and small cracks in its surface without greatly impairing the performance of the permeable vapor barrier (Straube, 2001), or defined by building codes as anything with a permeability of 1 perm or less (Lstiburek, 2000)	- Polyethylene sheet membrane (Visquene) or film (varying thicknesses, 2-6 mil and in 3-20 foot rolls) sealed with manufacturer recommended caulk, sealants, and tapes - EPDM - Plastic sheeting - Rubber membranes - Glass - Aluminum foil - Sheet metal - Oil-based paint - Bitumen or wax impregnated kraft paper - Wall coverings and adhesives - Foil-faced insulating and non-insulating sheathings - Vapor retarder latex paint - 2 coats of acrylic latex paint top coating with premium latex primer - 3 coats of latex paint - Scrim (open-weave fabric like fiberglass fabric) - Hot, asphaltic rubberized membranes - Some insulations (elastomeric foam, cellular glass, foil faced isofoam) if sealed - Aluminum or paper faced fiberglass roll insulation - Foil backed wall board - Rigid insulation or foam-board insulation - 1/4 inch Douglas fir plywood with exterior glue - High-performance cross-laminated polyethylene (Information from Lstiburek, 2000; ICAA, 2002; Spence, 1998; Bordenaro, 1991; Maness, 1991; Lotz, 1998; Lstiburek and Carmody, 1991; Forest Products Lab, 1949; DoE, 2002)
Air Barrier/ Pressure Threshold	"control airflow and thereby control convection vapor transport" (Straube, 2001), controls the moisture that is transported along with this airflow (Straube - vapor, 2002); helps to increase comfort, reduce energy consumption, help control odor, and help reduce sound transmission (Straube, 2001); and must be "continuous, durable, stiff (or restrained), strong, and air impermeable	- Unpainted gypsum board (sealed) - House-wrap, if properly sealed and continuous - Continuous building paper (15# or 30# felt paper) - Plywood - Foam board insulation - Hot, asphaltic rubberized membranes - Some insulations (elastomeric foam, cellular glass, foil faced isofoam) if sealed

	Definition	Sample Materials
	(Straube, 2001)	(Information from ICAA, 2002; DoE, 2002)

Now that these two barriers have been defined and some sample materials that qualify as air and vapor barriers have been listed, we can begin our discussion of why we would utilize these materials in a wall assembly.

The function of an air barrier is to stop outside air from infiltrating into the building through the walls, windows, or roof and to keep inside air from exfiltrating through the building envelope to the outside (Quiroutte, 1991). An air barrier may be utilized at any location within the wall assembly, but the designer must always consider the following points when designing an air barrier:

- Air barrier must be continuous throughout the building envelope. The wall must be continuous with the roof and must be connected to openings such as doors, windows, etc. (Quiroutte, 1991),
- Must be securely fastened to the structure to resist wind load, stack effect, and pressurization from mechanical systems (Quiroutte, 1991),
- It must be virtually "air-impermeable" (Quiroutte, 1991),
- Avoid air leakage, cracks, and holes in construction (Handegord, 1982),
- Air tightness must be designed, constructed, and maintained around all details (Handegord, 1982),
- Permeability of the material used as an air barrier must be determined (Rousseau, 1990),
- Ease of detailing and building a continuous assembly with the contract documents (i.e., Can it be built as designed?) (Rousseau, 1990),
- Sequencing of wall assembly during construction (Rousseau, 1990),
- Ease of inspection and performing maintenance once installed (Rousseau, 1990), and
- Material durability at the selected location (Rousseau, 1990).

An air barrier must be specifically designed, detailed, constructed and in order to ensure that it is effective (Rousseau, 1990). Since air leakage is the most significant mechanism to be considered in moisture control, it should be controlled regardless of climate. It should be remembered that air leakage moves far more moisture than vapor diffusion does through materials (Sherwood and Moody, 1989 and Letter, 2000). A key principle to be remembered with an air barrier is that they should be used everywhere, and they should be properly designed and subsequently constructed (Straube, 2002). A fine line exists because the reduction of air infiltration in homes today has helped create the moisture dilemma since wall systems hold more moisture than they used to because of better insulation and airtight construction techniques (U.S. Forest Service, 1949). The homes of decades past were able to breathe more (i.e., "the old drafty

house") and were better able to transpire and reduce the accumulated moisture being generated by our daily activities (Wetterman, 1982). It has been reported that a family of four produces 7.5-12 liters of moisture per day and that the comfort level for humidity in a house is only 2.5-3.5 liters of air-borne moisture within a 2000 ft^2 house (Wetterman, 1982). The excess moisture must be dealt with in our homes.

Air that leaks into a wall assembly must also have means to exit the assembly and, in most cases, can be corrected through careful detailing and maintaining quality control at the inlet openings and outlet openings are the sources of air leakage into wall assemblies (Lstiburek and Carmody, 1991). Inlet openings are typically unsealed electrical outlet boxes, bottom edges of interior gypsum board cladding, or openings/gaps/joints in interior air barrier systems. Outlet openings are joints between sheets of exterior sheathings, top plate and bottom plate connections to the exterior sheathings, service penetrations, and other construction flaws. These openings must be detailed and constructed correctly if the air barrier's integrity is to be maintained.

Major points to be considered with regards to air barriers are:

- Air barriers often act like vapor barriers due to the permeance of the materials used (Straube, 2002).
- The designer should consider whether or not the air barrier material qualifies as a vapor barrier because utilizing a redundant system will lead to harmful moisture issues within the wall cavity by trapping vapor inside layers creating an ideal environment for rot, decay, mold, and fungi to flourish in (Roger, 1964). Examples of easily incorporated inadvertent vapor barriers include vinyl wall coverings and multiple coats of paint (i.e., 3 coats of latex paint) that inhibit the wall's capacity to dry.
- In order for an air barrier to be totally effective, an airtight seal must be maintained between all elements that the air barrier comes into contact with (James, 2000).
- A vapor barrier may have holes, but the air barrier must be continuous and free of holes in order to control any unwanted water vapor movement (Lstiburek, 2000; DoE, 2002; Lstiburek and Carmody, 1991).
- The specific location of the air barrier within the wall cavity is not as important as the air barrier maintaining "intimate contact" with the insulation so that the cavity does not promote conditions that facilitate convection and the subsequent moisture generation problems associated with these air currents (Quiroutte, 1991).

Air leakage through a wall assembly nearly approaches zero in modern construction because of the rampant use of sealers and caulks between any and all the joints and materials (Straube,

2002). While the approach specified by most designers calls for the use of housewrap as the air barrier, they should be cautioned since this material has been shown in the DOE (2000), Holladay and Vara (2000), McDaniel (2000), Holladay (2000), Cushman (1997), and James (2000) articles to allow air to pass through once it has been stapled or attached by other means. While all the joints may be taped, as directed by the housewrap manufacturer, tapes, and sealants are prone to deterioration over time. A full discussion of housewrap cannot be adequately discussed for the brevity of this report (references for an initial investigation of housewraps has been included in the bibliography). The importance has been mentioned since housewrap is a critical component that must be considered and designed when dealing with moisture. Two principles should be remembered: 1.) "If all building assembly openings are controlled then air movement as well will be controlled" and 2.) A tight assembly equals less air movement, which equals less moisture movement (Lstiburek and Carmody, 1991). Once air movement is controlled, how the designer deals with and details for the potential moisture accumulation becomes the central concern in wall cavity design.

While the five subjects of 1.) evaporation, 2.) capillary suction, 3.) leakage, 4.) ventilation, and 5.) diffusion all seemingly act independent of one another, the areas must be designed, detailed, and constructed with an understanding of how each separate component's behavior affects the other. Failure to address each subject correctly could potentially lead to moisture related concerns within the cavity wall system. It has been reported "with the exception of structural errors, 90% of building construction problems (are) associated with water" (Trechsel, Achenbach, and Launey, 1982). We shall now investigate why vapor barriers, termed vapor diffusion retarders by ASHRAE (and to be referred to as vapor barriers from here forward), are used today and then we will look at how the literature reviewed says they should be used.

1.3.4 Why vapor barriers are used today?

A vapor barrier's performance is measured in *perms*, which is "the passage of one grain of water vapor per hour through one cubic foot of material at a pressure differential of one inch of mercury between the two sides of the material" (Allen, 1990). A vapor barrier is any material that has a permeance of less than or equal to 1 in residential construction, but this number is typically much lower for other types of construction (ASTM, 1999; Lstiburek, 2000). Materials that are intentionally utilized as a vapor barrier have a perm rating of .1 or less, even though the definition provides for less stringent permeance characteristics (DoE, 2002). To further prevent any trapping of moisture in the wall cavity, the cold side of the material should have a perm rating at least five times greater than the value at the warm side (DoE, 2002). The permeance of the vapor barrier becomes purely academic once a hole is made, therefore, any work occurring after the installation of the vapor barrier should be checked to ensure that no major tears, punctures, or

damage has disturbed its surface integrity (Lotz, 1998; Wilson, 1999). A vapor barrier should be included in the wall system design when the designer is seeking to create a moisture and infiltration tight environment for the wall system (Stein and Reynolds, 1992; Lstiburek, 2000). A vapor barrier is not a waterproofing application; it is a material with a low permeance that aims to slow or retard the movement of vapor through the material to prevent the vapor from reaching the dew point on another surface (Bordenaro, 1991; DoE, 2002; Kubal, 2000; ASTM, 1999; Quiroutte, 1991; DoE, 2002; Straube, 2002; Lstiburek and Carmody, 1991; ICAA, 2002).

The incorporation of a vapor barrier in the wall system can be looked at as a means of controlling condensation in wall assemblies. The vapor barrier is expected to control condensation, regardless of how the moisture entered the cold side of the assembly (Rousseau, 1990; Forest Products Lab, 1949). Stewart Rogers (1964) summarized prevention of condensation in buildings as "keeping the indoor air dry or keeping impervious interior surfaces warm or keeping moist air from coming into contact with cool surfaces." He enumerated six steps for accomplishing this task (Rogers, 1964).

1. "Get rid of excess moisture" through drainage, venting, and isolating moisture generating sources" (Rogers, 1964).
2. "Keep moist air away from cold surfaces" by using a vapor barrier or other vapor impervious materials (Rogers, 1964).
3. "Keep critical surfaces warmer than dew point temperature" by insulating the cold side and not using thermally effective material on the warm side of the vapor resistant components (Rogers, 1964).
4. "Allow water vapor within construction to escape through the cold side" by designing the outer skin with a vapor porous material or by using air vapor paths through vents in the skin (Rogers, 1964).
5. "Avoid vapor traps" by not using a double vapor barrier or unintended vapor barrier and using vented flashing in built-up roofs (Rogers, 1964).
6. "Use absorbent materials that can hold transient condensation harmlessly" by allowing air circulation over indoor surfaces to prevent and encourage reevaporation of any moisture the materials may acquire (Rogers, 1964).

The principles of vapor drive mentioned earlier, Section 1.3.3, pages 32-39, are a prime reason for incorporating a vapor barrier in the wall system design. In winter, the warm, moist interior air is drawn outward to the drier, cooler air by the differences in vapor pressure associated with negative vapor drive (Kubal, 2000). The opposite tends to occur in the summer when the moisture vapor travels from the moist and warm outside air to the cool, dry interior area called positive vapor drive (Kubal, 2000). Vapor drive within the cavity is the process through which

materials seek a state of equilibrium and move vapor to other parts of the wall system. A vapor barrier is useful in the battle against vapor drive and the moisture contained in the migrating air (Kubal, 2000).

If the building design provides for an air barrier and is constructed correctly with no openings, the airflow and its capacity to move water vapor into and through a wall system can be eliminated. Vapor diffusion must then be designed for and implemented in the structure because heat transfer, air transport, and vapor diffusion are the only means through which water vapor can move within a wall system (Lstiburek, 2000). The continuity of the vapor barrier is not as important as the continuity of the air barrier. However, the vapor barrier should be as impervious as possible, and continuity should be striven for since air movement should be minimized when aiming to control vapor movement (Lstiburek, 2000; Lotz, 1998; DoE, 2002). The effectiveness of the vapor barrier is said to be proportional to its continuity and integrity (i.e., a vapor barrier that has 10% of its surface area with openings is 90% effective against vapor diffusion) (Lstiburek, 2000). If the vapor barrier also fulfills the role of the air barrier, then the vapor barrier must be installed in the same manner as the air barrier in order to be effective in both roles.

If the wall system is detailed correctly, the flashing should be carried up and through the vapor barrier so that any condensation that does build up on the vapor barrier will have a designed path for the liquid condensate to exit the wall system (DoE, 2002). Vapor barriers stop the drying process, so there must exist a means of allowing water to be removed from the wall system (Straube, 2002). Storage capacity should be determined for each specific material that is to be used as a vapor barrier (Sherwood and Moody, 1989).

1.3.5 How do you use a vapor barrier?

In a cold climate, a vapor barrier should be installed as close to the warm side of the wall or thermal insulation as possible to aid in preventing water vapor from entering the insulation and condensing into liquid at the point where the air temperature inside the cavity drops and reaches the dew point (Stein and Reynolds, 1992; Allen, 1990; Kubal, 2000; Rogers, 1964; McGinley and van der Hoeven, 1999; Quirouette, 1991; Lotz, 1998; Sherwood and Moody, 1989). The application of a vapor barrier on the warm in winter side of the insulation tends to reduce the temperature and relative humidity of the structure (Rogers, 1964). Any material used on the cold side of the vapor barrier should see a rise in the permissible relative humidity and temperature of the wall section (Rogers, 1964). Typically a vapor barrier is a plastic film and is placed just behind the interior wall surfaces (gypsum board and flooring) (Stein and Reynolds, 1992). However, in hot, tropical areas the vapor barrier should be placed on the exterior side of the insulation to prevent condensation from wetting the insulation as the air migrates under positive

vapor drive (Kubal, 2000; Lotz, 1998). In mild, more temperate climates, a vapor barrier may or may not be necessary. The specific wall assembly design and climatic conditions should be calculated when deciding whether or not to use a vapor barrier regardless of the climate.

A vapor barrier may be accidentally or inadvertently installed in the wall system due to the many types of materials that qualify as a vapor barrier as seen in Table 5 in Section 1.3.3.5. All material permeance ratings should be checked prior to being installed in the wall system (Rousseau, 1990). Many materials that are used behave like a vapor barrier and often trap moisture within the wall system, which often leads to deterioration, mold and mildew growth, and/or corrosion if left uncorrected or unnoticed (Maness, 1991). The vapor barrier should be installed in a seamless, or as near to seamless, as possible manner to reduce air infiltration (Allen, 1990). The vapor barrier sheet application should be lapped and sealed to prevent any breaks in the barrier, and any holes or cracks should be sealed if the vapor barrier is to perform adequately in retarding moisture (Kubal, 2000; Maness, 1991). A vapor barrier is often attached as a finish to batt insulation material (for example, wax impregnated kraft paper), or the vapor barrier may be applied separately, which is often preferred by designers because of the fewer number of seams that have to be sealed during construction (Allen, 1992).

A vapor barrier should not be used in a waterproofing application role because of its low permeability. The vapor barrier does, however, act quite effectively at preventing and breaking the upward capillary movement of vapor into the pores of concrete by providing a contact break with the soil located sub-slab (Kubal, 2000; Lstiburek, 2000). According to Lstiburek and Carmody (1991), moisture is also prone to collect as condensation at the following interchanges where vapor barriers are often used:

- Insulation and sheathing
- Sheathing and building paper
- Building paper and cladding.

An air mass that is cooled below its dew point can no longer retain the vapor that is being carried and condensate may be formed (Allen, 1990). The specifics of where to locate the vapor barrier should be calculated for the specific climatic condition and the specific wall system as discussed and calculated earlier in Section 1.3.2.3. The particular orientation of the structure also plays a critical role in locating where, if, and when to utilize a vapor barrier. Each of the north, south, east and west facing walls have different design parameters due to the varying climatic conditions each orientation presents. The purpose for locating the vapor barrier near the interior surface, in most heating climates, is because the higher indoor air temperatures are capable of carrying more water vapor that can reach the dew point when the air current reaches the insulation (and

cools down) as the air passes through the wall cavity (Allen, 1990). In hot, humid warm weather climates, the vapor barrier should be located outside of the insulation and in other mild climates a vapor barrier may not even be needed (Allen, 1990).

The incorporation of a vapor barrier in a mixed climate is the area that remains most vague and for the most part neglected in the literature reviewed. The primary difference for determining whether to use a vapor barrier or not depends upon understanding the nature of vapor movement and the potential for drying within the specific wall system design. The ASTM recommends utilizing a flow-through design approach, and this approach closely follows other research and is logical for combating the moisture problem. The flow-through design approach acknowledges the fact that wetting will occur from one side of the wall system during one season, and that the wall system will allow drying in the next season from the opposite side. Following the flow-through approach for the mixed climate region of the country is the most logical approach from a design perspective. The design for these types of wall systems must be closely examined and investigated because the potential for creating a redundant or inadvertent vapor barrier system within the wall cavity creates the ideal environment for problems associated with vapor accumulation, such as mold, mildew, and ultimately decay.

The following is in specific reference to the roof, however, the principle also applies to the wall assembly as a whole. "The specific location of the vapor barrier in the wall system should be determined by calculating where the dew point is located in the system and then placing the vapor barrier at a location above the dew point, if the dew point is outside of the system, a vapor barrier may not even be needed" (Bordenaro, 1991). The geographic conditions (specific number of cooling and heating days) and orientation of the designed walls should be investigated and specifically designed for when considering the inclusion of a vapor barrier in the wall system (Allen, 1990). A vapor barrier should be located on the outside face of the insulation in hot, humid climates and on the inside face of the insulation in cold climates (Krogstad and Weber, 1999). As a general rule, the colder the climate the greater the need for a vapor barrier within the wall system (ICAA, 2002).

The codes (<u>CABO: One and Two Family Dwelling Code, 1995 Edition, Fourth Printing</u>, and <u>International Residential Code: For One and Two Family Dwellings</u>) call for the cold regions of the United States to use the vapor barrier on the interior of the building assembly since moisture tends to migrate from inside to outside (Lstiburek and Carmody, 1991). Wetting of the wall system tends to occur from the interior, and drying tends to occur towards the exterior in a heating climate. Therefore, a vapor barrier and air barrier should be installed towards the interior (Lstiburek, 2000). The purpose of locating the vapor barrier as prescribed by Lstiburek is to

prevent the wall system from becoming wet by interior sources. It is recommended that the exterior sheathings be made of permeable materials (Lstiburek, 2000). A sample wall section for this heating climate may be referenced in Figure 1.4.

The cooling climate (hot, humid) regions of the United States should have a vapor barrier installed towards the exterior of the building assembly because moisture tends to migrate from the outside to the inside (Lstiburek and Carmody, 1991). The role of the vapor barrier in this climate is to prevent the wetting of the wall assembly from the exterior due to the moist air drive from the exterior towards the cool, interior air (Lstiburek, 2000). Therefore, the vapor barrier and the air barrier system should be installed towards the exterior of the wall assembly (Lstiburek, 2000). The purpose of this design strategy is to facilitate drying towards the interior if the wall assembly were to get wet from moisture's infiltration. A sample design for a wall system for this climate can be seen in Figure 1.5.

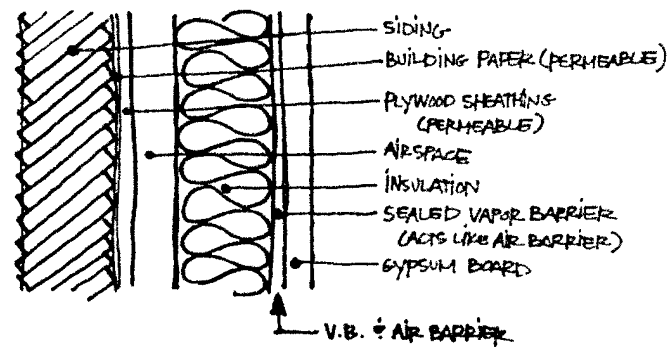

Figure 1.4, Sample heating climate wall section adapted from Rogers (1964), <u>Thermal Design of Buildings</u>

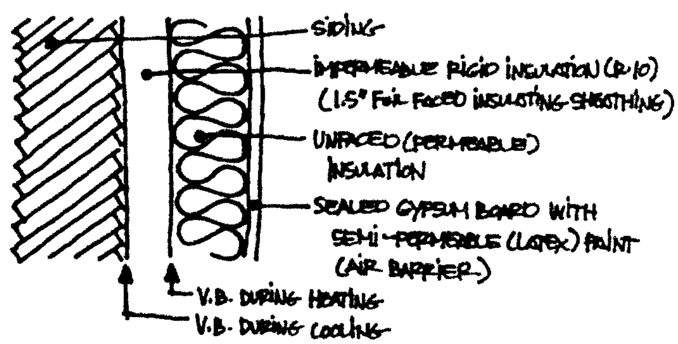

Figure 1.5, Sample cooling climate wall section adapted from Lstiburek (2000), <u>Builder's Guide to Mixed Climates: Details for Design and Construction</u>

The largest portion of the United States falls into the mixed climate region. The mixed climate region experiences one half of the year of inside to outside moisture movement and the other half outside to inside moisture movement (Lstiburek, 2000 and 2002). In this instance the design would necessitate a "flow-through" design approach, which is defined by ASTM as "unidirectional vapor flow in installations where any water vapor that diffuses into the insulation system is permitted to pass through without significant accumulation" (ASTM, 1999). The "flow-through" approach includes utilizing permeable and semi-permeable material on the interior and exterior surfaces (Lstiburek, 2000). An appropriate material would be kraft paper faced insulation installed towards the interior so that the kraft paper faced insulation

behaves to satisfy the "flow-through" conditions at the respective times of the year (Lstiburek, 2002). A sample "flow-through" wall may be seen in Figure 1.6. Another appropriate design approach for this climatic area would be to implement and utilize the normal assembly design implemented in either the cold or hot, humid climates. Designers utilizing this approach accept moisture accumulation in the wall assembly for part of the year and assume drying will occur during the other part of the year (Lstiburek, 2000). The last alternate design approach for this climatic region would be to install the vapor barrier (impermeable/semi-impermeable insulating sheathing on the exterior of the cavity wall system, like 1.5 inch foil-faced insulating sheathing) in the middle of the wall assembly (Lstiburek, 2000). A sample of this wall system designed for this climatic region can be seen in Figure 1.7.

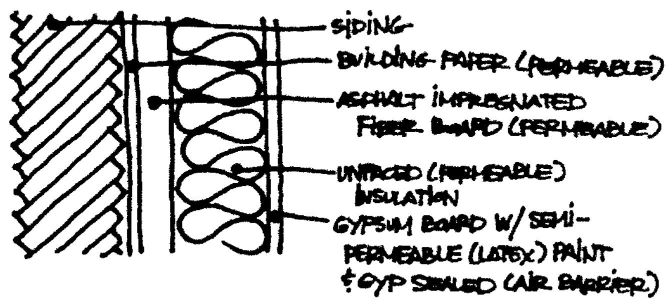

Figure 1.6, Sample mixed climate wall section adapted from Lstiburek (2000), <u>Builder's Guide to Mixed Climates: Details for Design and Construction</u>

Foundation design is an area that is often overlooked and poorly detailed during residential construction. Concrete is a permeable material and water migrates through concrete over time. An article written in *Concrete Products* in the "Contractor Talk" column points out that there are four conditions under which a vapor barrier should be implemented. The conditions are as follows:

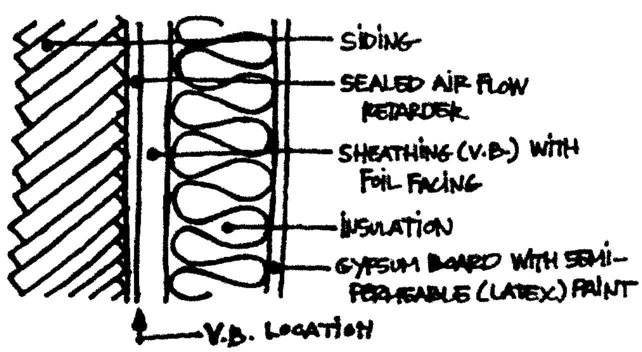

Figure 1.7, Sample mixed climate wall section adapted from Lstiburek (2000), <u>Builder's Guide to Mixed Climates: Details for Design and Construction</u>

"1. When an impermeable surface will be applied to the concrete surface, such as sealers or coatings,
2. When goods or merchandise stored on the floors is moisture sensitive,
3. When moisture on the floor will damage machinery, and
4. When installed flooring and adhesives are moisture sensitive." (Anonymous, 1993)

The article also stated two conditions under which the implementation of a vapor barrier would probably not be necessary:

"1. When the building sites are well drained and the water table is normally well below the ground surface elevation, a compacted layer of granular fill at least 4 in. thick can be placed in place of a vapor barrier. This has often been proven satisfactory when the floor coverings and adhesives are not moisture sensitive, and

2. Where no soil moisture problems exist or regions where irrigation, heavy sprinkling and high rainfall are not common." (Anonymous, 1993).

The implementation of uninsulated crawl spaces has led to an increased stack-effect vapor movement and in general a rise in overall moisture content within the wall (FPL, 1949; Lstiburek and Carmody, 1991). Uninsulated, bare earth crawl space often has condensation and moisture associated problems. Designers often combat this problem in the cold, mixed, and hot, humid areas using heavy roll roofing underlayment or by applying a membrane vapor barrier in the crawl space (FPL, 1949; Lstiburek and Carmody, 1991; ICAA, 2002). Implementation of a moisture cover over the ground in a crawl space will help to minimize the moisture migration into the structure from the ground below (ICAA, 2002). The correct height of the ventilated crawl space is one that would be sufficient for maintenance to be done. The crawl space should be properly graded for drainage and have adequate drainpipes to remove any water that may accumulate in this space away from the wall cavity (U.S. Forest Service, 1949).

The design of vapor barrier underlayment, as recommended by the American Concrete Institute, should include a 3-inch thick layer of sand or gravel over the vapor barrier before placing the concrete for the slab (Suprenant, 1994). Gravel with sand, to fill in the voids between the gravel pieces, is the preferred material since gravel would not be moved or displaced as easily during the placing of the concrete as a straight layer of sand (Suprenant, 1994; Anonymous, 1993). The recommended vapor barrier for the sub-slab location is a 4-6 millimeter polyethylene membrane or other membrane (EPDM if high durability is desired) with all joints lapped at least 6-inches (Suprenant, 1994; Anonymous, 1993; Lstiburek and Carmody, 1991; Rogers, 1964). During the placement of concrete, the vapor barrier should be protected from any punctures since a hole in the vapor barrier would allow the concrete to become a channel for the moisture movement that the vapor barrier was designed to prevent (Suprenant, 1994).

Many lawsuits are filed each year related to moisture problems that have originated at the juncture of the roof to the wall (Cash, 1993). The poor construction of the roof/wall joint is primarily due to poor detail design of the flashing and subsequent poor field construction because the laborers and/or designers do not understand the principles of water movement or are not able

to visualize a means of flashing the joint correctly because of the complexity of the design (Cash, 1993). Moisture and condensation are troublesome at this joint because of the potential for a redundant vapor barrier. The need for a vapor barrier in the roof or ceiling is not a universal solution, but should be evaluated just as the implementation of a vapor barrier should be elsewhere (Cash, 1993). The conditions in the roof/ceiling and the incorporation of a vapor barrier should be considered in conjunction with whether or not the space is ventilated (ICAA, 2002). A ceiling with a space above and proper ventilation may not require a vapor barrier (ICAA, 2002). The ICAA has reported, "if sufficient attic ventilation exists, condensation problems do not occur in most U.S. climates" (ICAA, 2002). Climates that should not be ventilated include hot, humid and cold, hostile, arctic/subarctic climates where moisture/condensation problems are induced through ventilation and the general inability for drying to occur (Lstiburek and Carmody, 1991). The codes (CABO: One and Two Family Dwelling Code, 1995 Edition, Fourth Printing and International Residential Code: For One and Two Family Dwellings) require less ventilation in attics and crawl spaces if a vapor barrier has been incorporated in the structure (Sherwood and Moody, 1989).

1.4 Summary

Moisture dissipation from within a wall is directly related to both air movement and vapor diffusion (Carll, 2000). The rampant use of intentional vapor barriers in residential construction is in many instances creating redundant vapor barriers systems within the wall cavities, thus trapping moisture and water that cannot escape. Even when the vapor barriers are not redundant, the placement is often times in the wrong location, which creates as many problems as redundancy. A vapor barrier's location should be carefully designed in relation to the specific wall design, climatic conditions, and orientation. In order to control moisture, designers and builders must look holistically at the indoor and outdoor atmospheric conditions as well as the design of the building system to create the appropriate foundation, walls, and roof interactions in the wall assembly (Carll, 2000). Regardless, the recommended placement of a vapor barrier cannot be universal.

The following points are what seem to be the most important and salient points discovered in the course of this literature review:

1. Air moves far more moisture through materials than diffusion.
2. In a cold climate, a vapor barrier should be installed as close to the warm side of the wall.
3. In hot, humid, and tropical areas a vapor barrier should be placed on the exterior (warm) side.
4. In mild, more temperate, climates a vapor barrier may or may not be necessary.
5. A vapor barrier in a basement should be implemented in the same manner as it was in the above-grade wall system.

6. A vapor barrier should be only used if needed, and the use should be determined for the specific wall system design, climate, and orientation (North, South, East, West) where the structure will be located.
7. A vapor barrier is a good ground cover below slab-on-grade, and it is important in crawl spaces. The vapor barrier should help reduce moisture transport through capillary movement from the soil into the structure.
8. The vapor barrier does not have to be impervious, but should be installed with as few imperfections as possible to prevent the flow of air.
9. Multiple layers of paint (the non-vapor retarding type, i.e., latex), 3+ coats, behave like a vapor barrier.
10. Wallpaper, especially vinyl wall covering, behaves like a vapor barrier.
11. The wall cavity should not be ventilated in hot, humid (cooling) climates.
12. The wall cavity should be ventilated in temperate and cold (heating) climates.
13. An air barrier is needed and should be designed into all structures, regardless of climate.
14. Care should be taken when installing an air barrier because the air barrier is only as functional as the air barrier's material integrity (i.e., be impervious to cuts, tears, punctures, rips, etc.).
15. House wrap is a greatly misunderstood material despite its prolific use in residential construction.
16. Ventilation requirements in the attic space or crawl space should not be reduced with the inclusion of a vapor barrier.
17. All walls are different and will behave differently depending upon where and how they are to be constructed.

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2.0 The Code Recommendations for Vapor barrier Implementation in Residential Construction: Do the recommendations make sense?

2.1 Introduction

Vapor barriers are often misunderstood and misused materials within the building systems that are utilized in residential construction. The standards as defined by the American Society of Testing Materials (ASTM), and in the codes of the Council of American Building Officials, CABO: One and Two Family Dwelling Code, 1995 Edition, Fourth Printing, and International Code Council, International Residential Code: For One and Two Family Dwellings provide the industry with certain recommendations and requirements of when, where, and if to utilize this material within a structure's foundation, wall, and ceiling/roof cavity designs. The code recommendations will be evaluated, and subsequent recommendations will be made for designers and builders who reference/use/adhere to the code requirements to make decisions regarding the potential implementation of vapor barriers for the specific location.

2.2 Standards defined by ASTM

The ASTM standards, C755, define the vapor barrier's primary function within the wall system as "to control the movement of diffusing water vapor into or through a permeable insulation system" (ASTM, 1999). The diffused movement of vapor into and through a wall system follows one of two flow patterns, unidirectional or reversible (ASTM, 1999). Vapor pressure difference is the driving factor in determining how vapor barriers are to be used since the greater the pressure differential, the greater the rate of diffusion through the assembly (ASTM, 1999). During the design phase, the expected pressure differences should be realistic, not estimated, when determining the vapor barrier requirements (ASTM, 1999). The general practices for building cavity design as stated in ASTM cover air-conditioned structures, wood frame construction, and the placement of the insulation in the wall system design.

ASTM defines unidirectional flow, as having a "water vapor pressure difference [that] is consistently higher on one side of the system than the other" (ASTM, 1999). In cooler climates, this vapor flow should include the design of the vapor barrier on the indoor, warmer, side of the wall insulation. Reversible flow is defined as having a "vapor pressure [that] may be higher on either side of the system, and it often changes with the seasons" (ASTM, 1999). Design for reversible flow conditions do not greatly influence where in the wall system the vapor barrier should be placed. The assumption is that drying will occur during the opposite season for which the barrier was placed within the cavity.

If a membrane retarder material is to be used within the cavity, the ASTM recommends using a retarder with a lower permeance if a five-foot (1.5 meter) wide roll is used, or using a vapor barrier/retarder with a higher permeance if a 20 foot (6.1 meter) width is installed (ASTM, 1999). The reason for the permeance difference, dependent upon the width of the roll, is due to the air penetration through the materials. The smaller width roll of membrane retarder would require a

lower permeance because there would be more laps, joints, and seams than the wider roll and thus more air entrained vapor would potentially be allowed to pass through these potential openings. Even with proper sealing of the laps, joints, and seams of the smaller width rolls, perfect construction quality should never be relied upon for installation, especially since sealants are prone to breakdown over time and the quality of installation cannot be relied upon to be "as recommended" by the manufacturer (which most design specifications indicate). When designing the cavity, low permeability insulation installed with sealed, vapor tight joints often acts like a vapor barrier within the wall. A redundant vapor barrier system should be avoided, but is often inadvertently constructed into the wall system design when a vapor barrier is purposefully used and when the permeability characteristics of the other utilized wall system materials is not researched or thoroughly understood.

The ASTM standards also recommend the implementation of an air barrier system within the wall cavity (ASTM, 1999). The potential for condensation should be investigated when designing the placement of the air barrier within the wall system (ASTM, 1999). The recommended placement of the air barrier within the cavity is on the warm side of the insulation and should be installed in a continuous, unbroken manner to prevent the uncontrolled movement of air through the wall system, as previously discussed in the literature review. The air barrier is only as useful as it is continuous.

A vapor barrier should be installed with all joints, holes, penetrations, and cuts being carefully sealed with the recommended manufacturer specific sealants or tapes in order to maintain the vapor diffusion resistance characteristics of the material (ASTM, 1999). The ASTM has defined two recommended vapor barrier design practice principles, flow-through and moisture storage. Flow-through design is supposed to eliminate the possibility of condensation within the insulation and should include the use of a highly permeable insulation within the cavity (ASTM, 1999). The purpose of the high permeability insulation is to allow vapor to flow through the insulation and condense, if the vapor is to condense, on the next lower permeable surface (ideally the vapor barrier) within the system where the liquid would either be drained or removed through ventilation. The moisture storage principle allows for some moisture accumulation within the system's insulation, but the rate of accumulation is small and low permeability insulation should be used (ASTM, 1999). The design utilizing the moisture storage principle assumes that moisture condensation quantities will not exceed the storage characteristics of the material before the moisture is removed from within the system.

When determining the vapor flow within the system, the calculations are very similar to the calculations made to measure the heat flow through the wall system, see Section 1.3.2.3, pages

27 – 31. The formula, as provided by ASTM (1999), for calculating vapor flow through the wall system is:

$$\text{Vapor flow} = \frac{\text{Vapor pressure difference (between interior and exterior)}}{\text{Vapor flow resistance}}$$

The vapor pressure differentials in summer tend to cause vapor to flow in an inward direction, and as such, a vapor barrier should be used on the outer side of the insulation and facing the exterior covering of the structure (ASTM, 1999). The ASTM guidance goes on to state "the vapor retarder should still be located on the side of the insulation facing the interior of the building to control vapor flow under the more severe conditions" (from the warm winter side of the system) (ASTM, 1999). The guidance continues, stating that if an impermeable insulation material is utilized, a separate vapor barrier is not needed at all as long as the "joints (if any) are made impermeable by suitable sealing methods" as recommended by the manufacturer (ASTM, 1999). The standard includes a statement regarding residential construction and the implementation of a totally separate system. The wall system must be designed for moisture that penetrates the retarder, then moves into the insulation, and finally continues on to the outside through some means of ventilation or forced air movement within the cavity (ASTM, 1999). The ASTM standards provide design solutions/recommendations to effectively handle all climatic conditions encountered in the United States construction process, and they provide designers and builders with a clear understanding of how to correctly utilize these materials in the wall systems.

2.3 CABO and ICC Code Summaries

The current residential building codes, as published by the Council of American Building Officials (CABO) and the International Code Councils (ICC), that have been investigated with regards to the implementation of vapor barriers are for residential one and two family dwellings. The applicable code sections from these references have been tabularized in summary form in Table 2.1 below.

Table 2.1, Vapor barrier specific code summaries, adapted from CABO (1995) & ICC (2000)

Section	Code	Title	Discussion
321	CABO	"Moisture Vapor Retarders"	- Required in all frame walls and floors, and ceilings, not ventilated to allow moisture to escape. - Vapor barrier to be used on warm-in-winter side of thermal insulation with two (2) exceptions: 3.) Where moisture or its freezing will not damage the materials. 4.) Hot, humid climates: 67°F+ wet bulb temps for 3000+ hours or 73°F+ wet bulb temp for 1500+ hours during warmest six (6) consecutive months of year.

Section	Code	Title	Discussion
R322	ICC		- In all framed walls, floors and roofs/ceilings comprising elements of building thermal envelope. - A vapor barrier shall be installed on warm-in-winter side of insulation with three (3) exceptions: 4.) Where moisture or its freezing will not damage the materials. 5.) Hot, humid climates: 67°F+ wet bulb temps for 3000+ hours or 73°F+ wet bulb temp for 1500+ hours during warmest six (6) consecutive months of year. 6.) Counties listed in ICC Table 1101.2, p.72-80 (summarized in report's table 2).
406	CABO	"Foundation Waterproofing and Dampproofing"	- No discussion other than waterproofing applications and moisture barrier installation
R406	ICC		
409	CABO	"Crawl Space"	- When ground surface is treated with a vapor barrier, ventilation opening requirements may be reduced to 1/1,500 of the under-floor area, or - Ventilation openings may be omitted when continuously operating mechanical ventilation is provided at a rate of 1.0 cfm for each 50 ft^2 of crawl space and the ground surface covered with a vapor barrier.
R408	ICC	"Under-Floor Space"	- Same two rules/exceptions as CABO, plus - Ventilation openings not required if ground covered with a vapor barrier, space is supplied with conditioned air, and perimeter walls are insulated.
505	CABO	"Concrete Floors (on ground)"	- Vapor barrier with joints lapped at least six inches (6") shall be placed between slab and base course or prepared subgrade if no base course exists - Three (3) exceptions: 4.) Detached structures that are to be unheated (i.e., garages). 5.) Flatwork not likely to be enclosed and heated later (i.e., sidewalks, patios). 6.) As approved by building official.
R506	ICC		Exact words and requirements described in CABO
806	CABO	"Roof Ventilation"	Net free cross-ventilation area may be reduced to 1 to 300 with installation of vapor barrier (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling.
R806	ICC		Exact words and requirements described in CABO
		It should be noted that both CABO and the ICC state, with identical language, that "the total net free ventilating area shall not be less than 1 to 150 of the area of space ventilated except that the total area is permitted to be reduced to 1 to 300, provided at least 50% and not more than 80% of the required ventilating area is provided by ventilators located in the upper portion of the space to be ventilated at least 3 ft. above the eave or cornice vents with the balance of the required ventilation provided by eave or cornice vents."	
907	CABO	"Built-up Roofing"	- Vapor barrier to be installed between deck and insulation where average January temperature is below 45°F, or - Where excessive moisture conditions anticipated within the building.
R907	ICC		- Nothing vapor barrier specific

The information that is presented in Table 2.2 has been adapted and condensed from the ICC, Section R322, Table 1101.2, pages 72-80. The exact counties/parishes listed should be referenced when designing or constructing a structure in these states, and an exemption is being sought for moisture vapor barrier inclusion on the warm in winter side of the insulation.

Table 2.2, Adapted from information from ICC (2000): Section R322, Exception 3	
State	Number of counties exempted from warm-in-winter V.R. installation
North Carolina	16 of 100 counties
South Carolina	30 of 46 counties
Georgia	109 of 159 counties
Florida	All counties
Alabama	47 of 67 counties
Mississippi	64 of 82 counties
Louisiana	All parishes
Arkansas	44 of 75 counties
Tennessee	2 of 95 counties
Oklahoma	6 of 78 counties
Texas	139 of 254 counties

The two codes have similar intended audiences (one and two family dwelling designers and builders), and the requirements with regards to vapor barriers are nearly identical in both language and verbiage. Both of the codes dictate to the designer or builder where the vapor barriers will be placed with the exception of the section on concrete floors (on ground) where the provision, "or as approved by building official" is included.

The requirements, as outlined in the codes, are fairly specific with regards of where, when, and how to install vapor barriers within the wall systems. The code requirements do not easily allow proposals for acceptable alternatives by designers and builders who may be implementing alternative approaches to construction.

2.4 What the codes should say...foundation, wall, and ceiling/roof

2.4.1 Foundation – slab

The accumulation of moisture through the foundation/support elements (slab, basement, crawl space, etc.) is the primary point of entry into residential construction assemblies (Suprenant, 1994). The incorporation of vapor barriers in the foundation design is only as effective as the drainage mechanisms facilitate and allow. Designing proper drainage includes not only collecting water, but also effectively moving water away from the structure so that it does not accumulate and then migrate or be sucked up and into the wall system. The proper drainage requirements are dictated by the specific site conditions. An attempt to cover the drainage requirements will not be discussed at this time, other than to enforce the fact that drainage is a critical element for the design of the foundation system.

The placement of the sub-slab vapor barrier performs a dual role in the structure's moisture protection. The first role is to break capillary movement of moisture upward and into the

structure's assembly (Lstiburek and Carmody, 1991). Capillary break points should be designed into the entire foundation system for the many reasons discussed in the literature review Sections 1.3.2.2 and 1.3.3.1. The utilization of the vapor barrier to break capillarity and in these locations provides the building with this first preventative measure in dealing with moisture and minimizing the potentially harmful effects within the structure.

The second role of the sub-slab vapor barrier is to help prevent moisture migration through the porous concrete (Suprenant, 1994). The vapor barrier material for this application may include sheet polyethylene, dampproofing material, multiple layers of roofing paper, or EPDM sheeting. All joints should be lapped at least six (6) inches, and the vapor barrier material should be as impervious as possible to any breaks, punctures, or other such penetrations (Suprenant, 1994). Any and all openings should be sealed with an appropriate sealing material as recommended by the particular vapor barrier manufacturer. The role of the vapor barrier in this particular application should be designed and constructed in a similar manner as an air barrier within the wall system. The vapor barrier should be placed on top of, and in direct contact with, the compacted subgrade material. Then, on top of the vapor barrier and below the concrete slab, a three (3) inch thick layer of sand or varied sizes of gravel should be applied and lightly compacted (Suprenant, 1994). Gravel is recommended over sand because gravel is less easily displaced during the placement of the concrete slab and provides a consistently more uniform surface for the slab's placement. A discussion with Joe Vinson, a residential house builder, reveals that this layer is seldom used in residential construction because of the significant cost, and the perceived benefits of incorporation do not outweigh the increased cost of installation (Vinson, 2003). Special care and oversight should be taken during the concrete placement phase since the vapor barrier's effectiveness is proportional to the integrity of the retarder membrane below. The usage of a sand/gravel break between the vapor barrier and the concrete helps to prevent several problems that are often experienced when the concrete is placed in direct contact with the vapor barrier. The break between the vapor barrier and the concrete allows for speeding up the time between placement and finishing, helping to reduce the effects of cracking, improving the slab's strength, and helping to eliminate slab curling which may be experienced when concrete is placed in direct contact with the vapor barrier (Suprenant, 1994).

The requirements as outlined in the CABO and ICC codes make recommendations for the incorporation of vapor barriers in the on-grade sub-slab section that is in line and follows the recommendations and guidance as discovered during the review of literature.

Graphical detail drawings of the slab-on-grade foundation may be found in Figure 2.1.

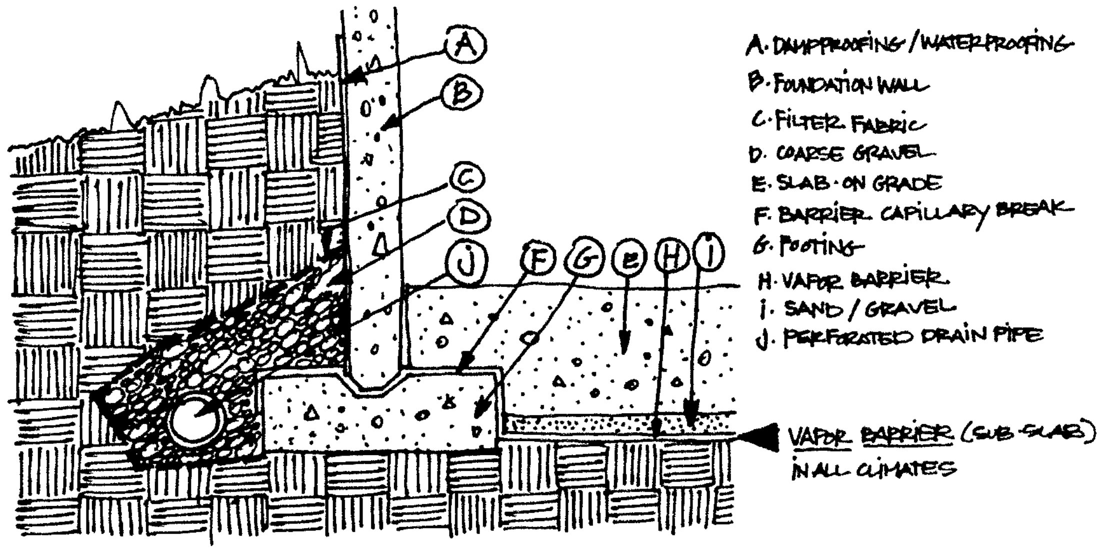


Figure 2.1, Adapted standard slab-on-grade and basement detail from Ramsey and Sleeper (1992).

2.4.2 Foundation – crawl space

The next aspect of the foundation system that would need a vapor barrier, according to the codes, is in the crawl space design that exists in many pier-post structures and other raised structures including basements. The crawl space design is very similar to that of the sub-slab vapor barrier. The same types of vapor barrier materials should be utilized in the crawl space area, as in the slab-on-grade, but it may be necessary to cover the vapor barrier with either a soil or gravel cover to prevent the vapor barrier from being moved. The ground cover vapor barrier should follow the same design and installation requirements as an air barrier (i.e., seal and lap all joints). The ground-cover vapor barrier should be attached to the structure's support columns or perimeter wall, if the space is enclosed. At all locations where the support columns or perimeter walls intersect the wall system, the vapor barrier design should include a membrane to provide a designated location to break capillary movement. The crawl space design should include a properly designed drainage system to include grading to prevent ponding that may occur should water pass through the crawl space. Ventilation of the crawl space is also necessary to help prevent moisture from accumulating in an unvented space that could migrate up and into the structure.

The codes state that "when [the] ground surface is treated with a vapor barrier, ventilation opening requirements may be reduced to 1/1,500 of the under-floor area, or ventilation openings may be omitted when continuously operating mechanical ventilation is provided at a rate of 1.0 cfm for each 50 ft^2 of crawl space and the ground surface covered with a vapor barrier" CABO,

1995 and ICC, 2000). The code allowed reduction does not follow the literature recommendations that were reviewed in the previous chapter. The purpose of the vapor barrier within this space proves to be very effective at combating the accumulation of moisture within the substructure that could then be pulled or transported up and into the structure. The opinion of the author is that maintaining the original recommended ventilation requirements in the crawl space, with or without a vapor barrier, is a necessity for residences. Ventilation in this semi-enclosed space is important should this space become wet. Drying can be facilitated through proper ventilation and moisture accumulation can be minimized and removed.

Graphical detail drawings of the crawl space foundation may be found in Figure 2.2.

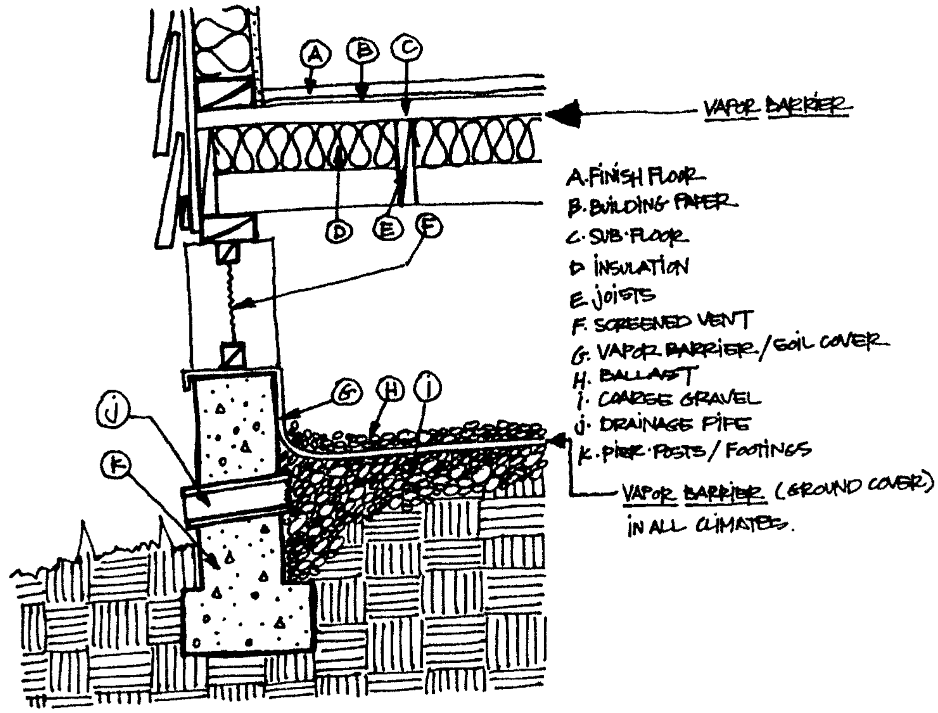


Figure 2.2, Adapted standard crawl-space detail from FPL (1949) and Ramsey and Sleeper (1992).

2.4.3 Foundation – basement

The design of the basement walls with regard to moisture is another problematic area that changes with regard to the particular building design. Basement slab design should follow the same design guidance that was provided in Section 2.4.1 with respect to sub-slab design. Due to the presence of high quantities of construction water that migrate out of the concrete basement walls over the first six (6) plus months, it is recommended that the basement walls not be insulated or finished during this time period. Allowing the basement walls to cure and expel this

construction water from the structure will help eliminate many of the problems that finished basements are prone to encounter. A preventive measure for the basement footings is to design a capillary break using a vapor barrier between the footing and the vertical basement wall (Lstiburek, 2000). Other than the standard dampproofing and waterproofing applications applied to the exterior surfaces of the basement walls, no other vapor barrier treatments are needed or required in these systems since the drying characteristics of the wall will vary significantly with the seasons. A vapor barrier would not facilitate the flow-through principle that should be utilized in basements. It should be noted, though not the opinion of the author, that the literature reviewed does recommend following the example of what was done above grade should be implemented below grade (i.e., if a vapor barrier was incorporated on the inner portion of the above grade wall then one should be used at the same location in the below grade basement wall system).

Graphical detail drawings of the basement foundation may be found in Figure 2.1 in Section 2.4.1 above.

2.4.4 Walls

The use of a vapor barrier in a wall assembly is an often confusing and wrongly accomplished detail that may lead to many moisture problems within assemblies. The application of the vapor barrier within the wall system design is greatly dependent upon where the structure is climatically, the orientation of the wall, and the wall system design. It should be noted that when a vapor barrier is installed incorrectly or redundantly the vapor barrier might become a vapor trap. Many materials behave like a vapor barrier within the wall cavity and all material permeance ratings should be investigated before designing or constructing the wall. ASTM states, "for practical purposes it is assumed that the permeance of an adequate retarder will not exceed 1 perm, although at present this value may be adequate only for residential construction" (ASTM, 1999). The climatic regions for residential design that this report will follow are in line with the ones presented by Lstiburek and Carmody and are labeled as heating climates, mixed climates, and cooling climates. The climatic regions are identified in Table 1.1, Section 1.3.1, of the literature review, but the characteristics are resummarized as follows:

- *Heating climate* is defined as an area that has 4000+ heating degree-days (Lstiburek and Carmody, 1991).
- *Mixed climate* is an area that has up to 4000 heating degree-days (Lstiburek and Carmody, 1991).
- *Cooling climate* is defined as an area that has 67°F or higher WB temperatures for 3000+ hours during the warmest 6 consecutive months and/or 73°F or higher WB temp for 1500+ hours during the warmest 6 consecutive months (Lstiburek and Carmody, 1991).

The implementation of a vapor barrier within the wall system of the residence built in a heating climate should follow the guidance that a vapor barrier should be installed on the inside of the wall insulation. The recommendations made in both the CABO and ICC codes follow this guidance fairly closely, although the number of heating degree-days varies slightly. The specific wall system design should be analyzed in more detail by utilizing psychrometric charts and investigating how the wall system temperature drops at each material change to determine where and if to incorporate a vapor barrier. The specific points where the dew point is reached within the cavity should be determined, and the vapor barrier incorporated as appropriate in a heating climate for each specific wall design.

A vapor barrier within the cavity of a wall system built in a cooling climate, or one which is typically classified as a hot and humid weather location, should place the vapor barrier on the outside (towards the exterior) of the wall system's insulation. Although the conditions for these locations would qualify as an exemption in the CABO and ICC codes (with the same slight deviation in the specific number of wet bulb temperatures) for placement on the warm-in-winter side, the codes recommendations are vague as to exactly where the vapor barrier should be placed within the wall system. The ICC does provide a very thorough listing of counties within each of the states in the United States that would qualify under this code exemption. Both codes should state that the vapor barrier should be located on the side of the insulation facing the structure's exterior if any of the exemption rules qualify.

The incorporation of a vapor barrier in a mixed climate is the area that remains most vague and for the most part neglected in the code requirements and in the literature reviewed. The primary difference for determining whether to use a vapor barrier or not depends upon understanding the nature of vapor movement and the potential for drying within the specific wall system design. The ASTM recommends utilizing a flow-through design approach, and this approach closely follows other research and is logical for combating the moisture problem. The flow-through design approach follows the principle discussed in the literature review, Section 1.3.5, pages 41 – 47. This approach acknowledges the fact that wetting will occur from one side of the wall system during one season, and that the wall system will allow drying in the next season from the opposite side. Following the flow-through approach for the mixed climate region of the country is the most logical approach from a design perspective. The design for these types of wall systems must be closely examined and investigated because the potential for creating a redundant or inadvertent vapor barrier system within the wall cavity creates the ideal environment for problems associated with vapor accumulation, such as mold, mildew, and ultimately decay.

The codes need to make recommendations for vapor barriers within the wall systems that are more climatically specific and address the permeability issues of the other materials that are utilized in the wall systems. Redundant vapor barrier systems are often inadvertently installed during construction, preventative maintenance, and renovation. Several examples of the incorporation of unintended vapor barriers include multiple, as few as three, coats of paint (non-vapor retarder latex specific), two coats of acrylic latex paint with premium latex primer underneath, vinyl wall coverings or wallpaper, the various adhesives used with wall coverings, foil faced plywood/OSB, bitumen/wax impregnated kraft paper, aluminum or paper faced fiberglass roll insulation, and using 1/4-inch Douglas fir plywood with exterior glue, etc (Lstiburek, 2000; ICAA, 2002; Spence, 1998; Bordenaro, 1991; Maness 1991; Lotz, 1998; Lstiburek and Carmody, 1991; Forest Products Lab, 1949; and DoE, 2002).

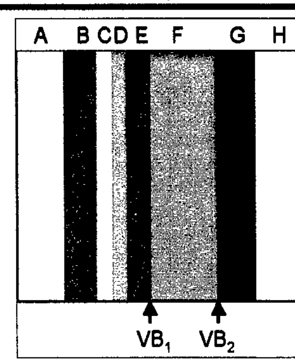
The recommendations for several wall section systems are summarized in Table 2.3 below. The discussed wall sections incorporate the following components: wood siding, aluminum siding, brick veneer, plaster veneer, and concrete shell. The various sections will be described with generic section solutions in the "Model Wall Section/Type" column. The respective climatic area columns will be used to discuss where the vapor barrier or other wall section revisions should be incorporated if one of these sections were utilized in the particular climatic area.

Table 2.3, Various Wall Section V.B. Applications According to Climate

Wall Type ***(Description abbreviation follows key/diagram at bottom)***	***Heating Climate***	***Mixed Climate***	***Cooling Climate***
Wood siding model: (A, B_1, C_1, D, E, F, G, & H)	Incorporate VB_2 between F and G	Vapor barrier not needed	Incorporate VB_1 between E and F
	Recommend using a polyethylene sheet membrane vapor barrier material	If vapor barrier used then place it at VB_1. Not recommended because of the added cost and high probability of redundancy.	Vapor barrier incorporation of a "Smart Vapor Barrier", or bitumen or wax impregnated kraft paper, instead of a polyethylene sheet membrane recommended
	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction	An air barrier should be incorporated, location not critical	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction
Brick veneer model (light wood frame): (A, B_2, C_1, D, E, F, G, & H)	Incorporate VB_2 between F and G	Vapor barrier not needed	Incorporate VB_1 between E and F
	Recommend using a polyethylene sheet membrane vapor barrier material	If vapor barrier used then place it at VB_1. Not recommended because of the added cost and high probability of redundancy.	Vapor barrier incorporation of a "Smart Vapor Barrier", or bitumen or wax impregnated kraft paper, instead of a polyethylene sheet membrane recommended
	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction	An air barrier should be incorporated, location not critical	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction
Plaster-like veneer (may include Dryvit® or EFIS systems) model on light wood frame: (A, B_3, C_2, D, E, F, G, & H)	Avoid this exterior finish system in this climate. Vapor barrier would be located in wrong location due to material properties of C and D.	Exterior wall system (C and D) already behaves like a vapor barrier and this system's use should be avoided in this climate. If used, then construct like in cooling climate.	No vapor barrier needed, since the combination of C and D behave like a vapor barrier.
	However, if this wall system is utilized in this climate proper ventilation and clear weep holes within this wall cavity design is necessary to allow water to exit the cavity or to dry.	An air barrier should be incorporated at the E and F intersection. If this wall system is utilized in this climate proper ventilation and clear weep holes within this wall cavity design is necessary to allow water to exit the cavity or to dry.	An air barrier should be incorporated at E during design and then correctly and carefully installed during construction

Note: All R-values were obtained from Stein and Reynolds (1992), pages 136-143, with the exception Durarok that was obtained from manufacturer's spec.

Light Wood Frame Construction Wall Section Composition Descriptions. (material thickness and R-value)	
A – *Outside Air* (Not applicable, .17 winter & .25 summer)	**E** – *Plywood* , Douglas Fir (1/2", 0.62)
B_1 – *Wood Siding* , back-primed (1/2", 0.81)	**F** – *Insulation* , Unfaced rolled batt (3-1/2", 11)
B_2 – *Brick* , common (2-2/3", 0.2)	**G** – *Gypsum Board* , primer coat and one latex coat (5/8", 0.56)
B_3 – *Stucco* , plaster/stucco/Dry-vit®/etc (1/2", 0.1)	**H** – *Inside Air* , air-conditioned (Not applicable,0.68)
C_1 – *Air cavity* (1/2", 1.35)	**VB_1** – Cooling climate vapor barrier location and **mixed climate vapor barrier location if used,not recommended**
C_2 – *Durarok®* or similar product (1/2", 0.26)	**VB_2** – Heating climate vapor barrier location
D – *Building Paper* , 15#, 30#, permeable housewrap, etc. (Negligible, 0.06)	



Graphical detail drawings of the wall section described above may be found in Figures 2.3 to 2.6.

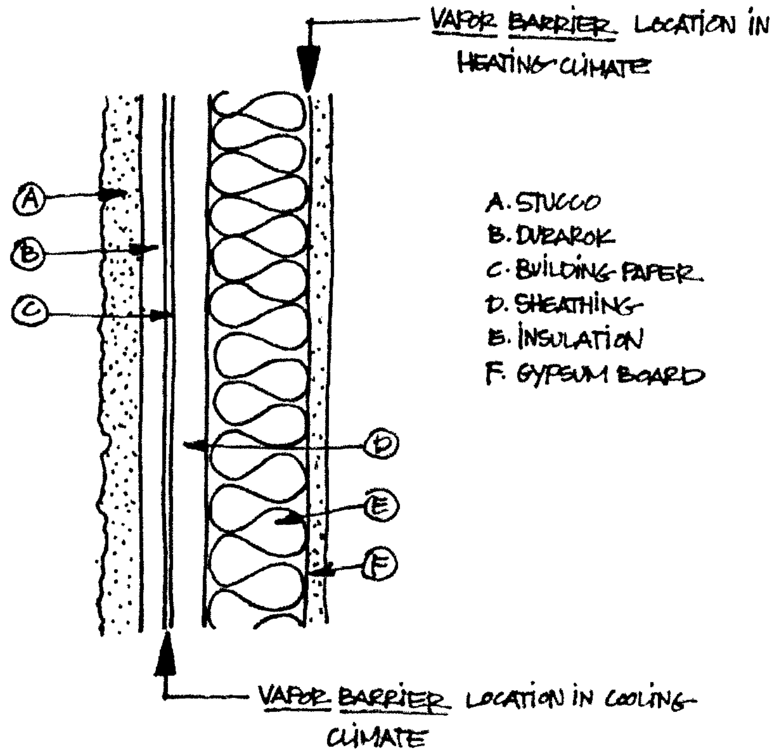


Figure 2.3, Adapted standard stucco veneer detail from Ramsey and Sleeper (1992).

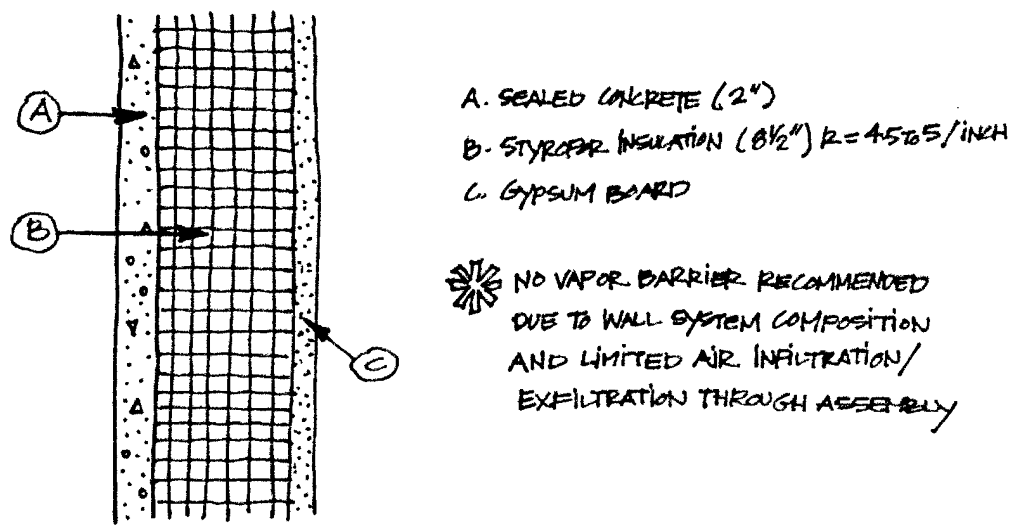


Figure 2.4, Holistic House Wall Section provided by Yvan Beliveau.

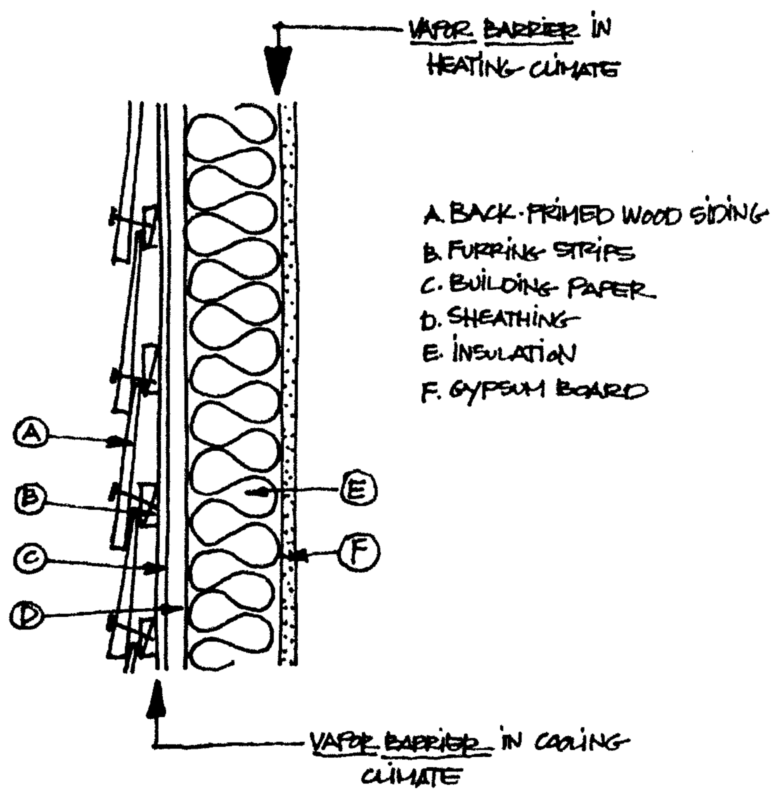


Figure 2.5, Adapted standard wood-siding detail from Ramsey and

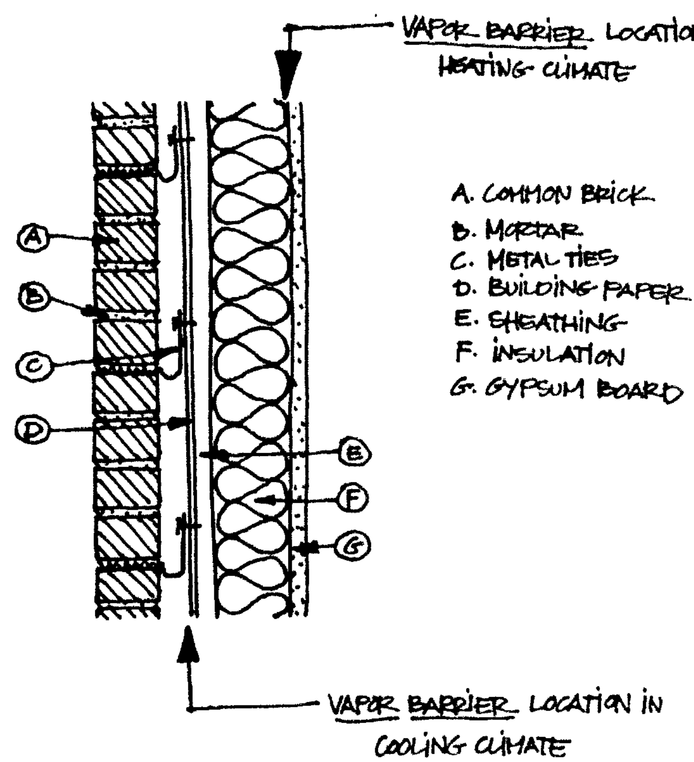


Figure 2.6, Adapted standard brick veneer on light-wood frame detail from Ramsey and Sleeper (1992).

2.4.5 Roof/Ceiling

The use of a vapor barrier in the roof/ceiling components of the assembly is effective and recommended as a means of being able to reduce the ventilation requirements in this part of our assembly according to the codes. The specifics of utilizing, or not utilizing, a vapor barrier in this area of the assembly is dependent upon the climatic area of the structure, the design of the ceiling/roofing connection, and whether or not the roof is ventilated. All of these items must be considered in conjunction with one another and cannot be looked at or designed in isolation when making a determination for when to utilize a vapor barrier.

The United States Forest Service published a pamphlet in 1949 that clearly explained the vapor barrier requirements according to the various climatic regions of the United States and the varying types of roofs (flat, gable/hip with no occupancy, and gable/hip with occupancy). The 1949 pamphlet's format served as the template for Table 2.4 that was developed to help explain the roof design recommendation in this report.

Table 2.4, Various Roofing V.B. Applications According to Climate

Roof Type	*Heating Climate*	*Mixed Climate*	*Cooling Climate*
Flat Roof	- V.B. may be installed between deck and insulation, if design calculations prove its necessity	- V.B. should be installed between deck and insulation, if the winter temps are as discussed in codes and design calculations necessitate incorporation	- V.B. not needed
Roof with Attic	- Super low permeance plastic sheet V.B. & air barrier designed between built-up roofing and insulation in 8000+ heating degree day climates - Higher permeance V.B. & air barrier designed between built-up roofing and insulation - Circulation/venting must be provided - Design calculations must be utilized to determine inclusion or exclusion	- Higher permeance V.B. & air barrier designed between built-up roofing and insulation - Circulation/venting must be provided - Design calculations must be utilized to determine inclusion or exclusion	- V.B. should not be used in this climate - Air circulation/venting sufficient in hot, dry environments - Air circulation/venting should be avoided due to high moisture concentrations in hot, humid environments - Air barrier designed to prevent air leakage
Cathedral Ceiling	- V.B. installed below the insulation (in the interior side of insulation) - Ventilation at the eave and ridge vented - Design calculations must be utilized to determine inclusion or exclusion	- V.B. installed below the insulation (in the interior side of insulation) - Ventilation at the eave and ridge vented - Design calculations must be utilized to determine inclusion or exclusion	- V.B. not necessary - Ventilation requirements same as attic space and should occur at eave and ridge if ventilated

Note: The CABO and ICC codes state, "[n]et free cross-ventilation area may be reduced to 1 to 300 with installation of vapor retarder (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling."

A great deal of debate is present in the literature that has been reviewed, and no firm consensus has been reached across all the material reviewed with regards to vapor barriers in the roof system. The only firm conclusion with regards to the inclusion or exclusion of vapor barriers in the roof design is to calculate the specific point where the dew point is reached within the roof system. The influence of air movement must be considered and the potential for drying through air movement to the interior or exterior of the roofing system materials. The designer must also be cognizant of the fact that if a vapor barrier is included and the roof develops a leak, the vapor barrier could behave as a vapor trap and cause the system to retain the water by not allowing it to escape.

The codes state that the "[n]et free cross-ventilation area may be reduced to 1 to 300 with installation of vapor barrier (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling" (CABO, 1995 and ICC, 2000). The allowed reduction does not appear to make any sense for the climatic areas where roof ventilation is required. One of the purposes of roof ventilation is to allow the space to dry out should the space below the roof become wet, and reducing the ventilation requirements would hamper this needed process. The opinion of the author is that the codes allow reduction of ventilation within the roof cavity is not recommended. The ventilation of the roof is necessary in effectively combating moisture accumulation in a heating area but not in a cooling environment.

Graphical detail drawings for the roofing applications described above may be found in Figures 2.7 to 2.9 below.

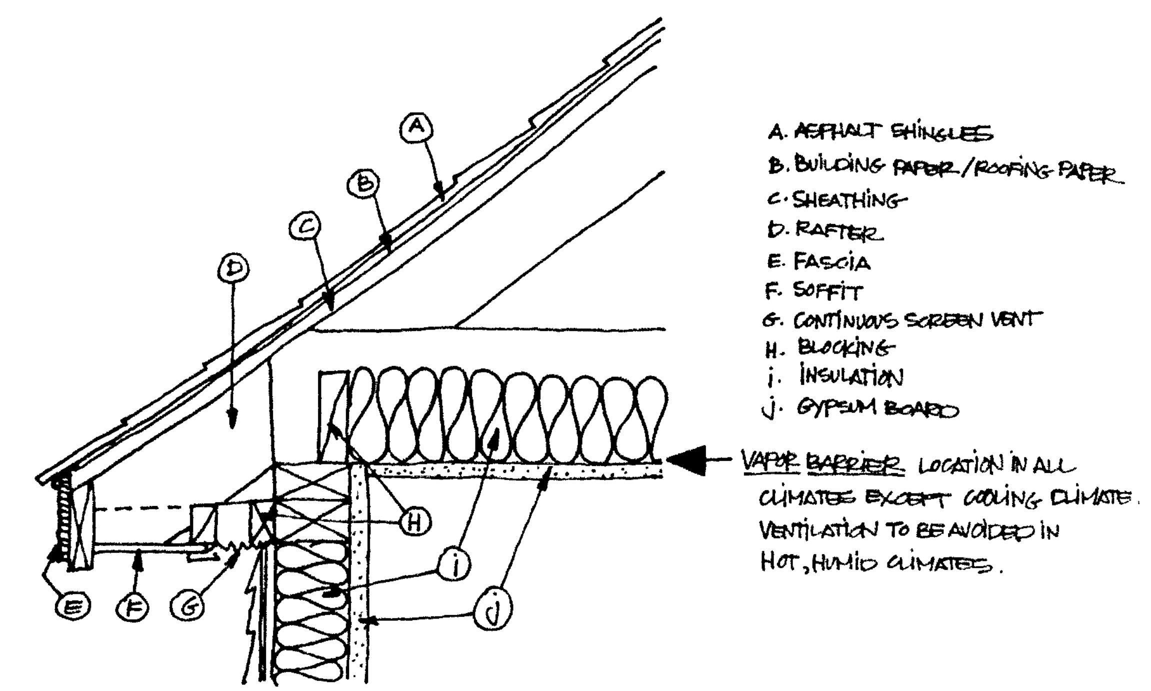


Figure 2.7. Adapted standard roof with attic detail from Ramsey and Sleeper (1992).

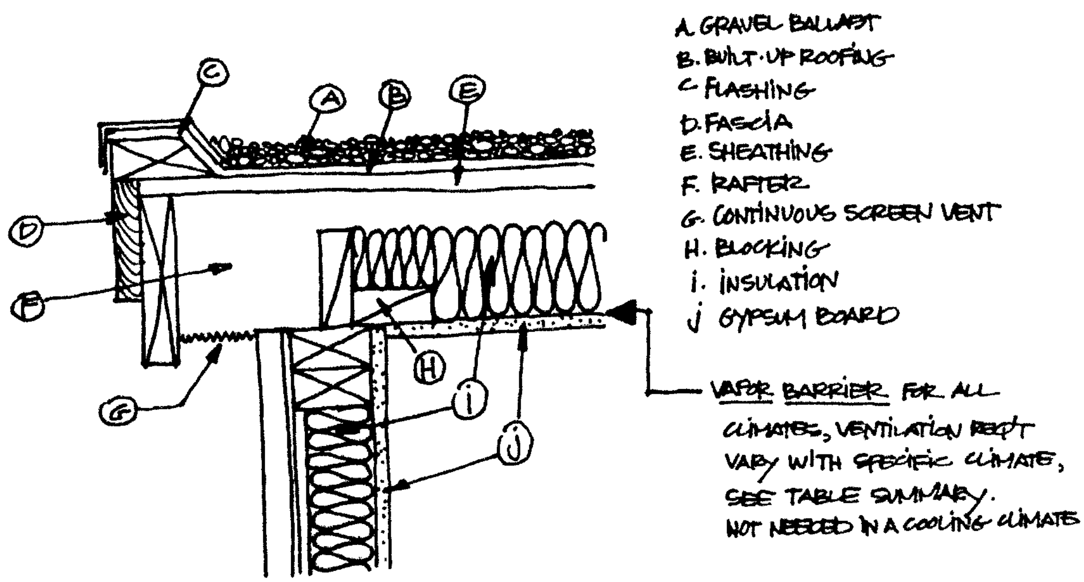


Figure 2.8, Adapted standard flat-roof detail from Ramsey and Sleeper (1992).

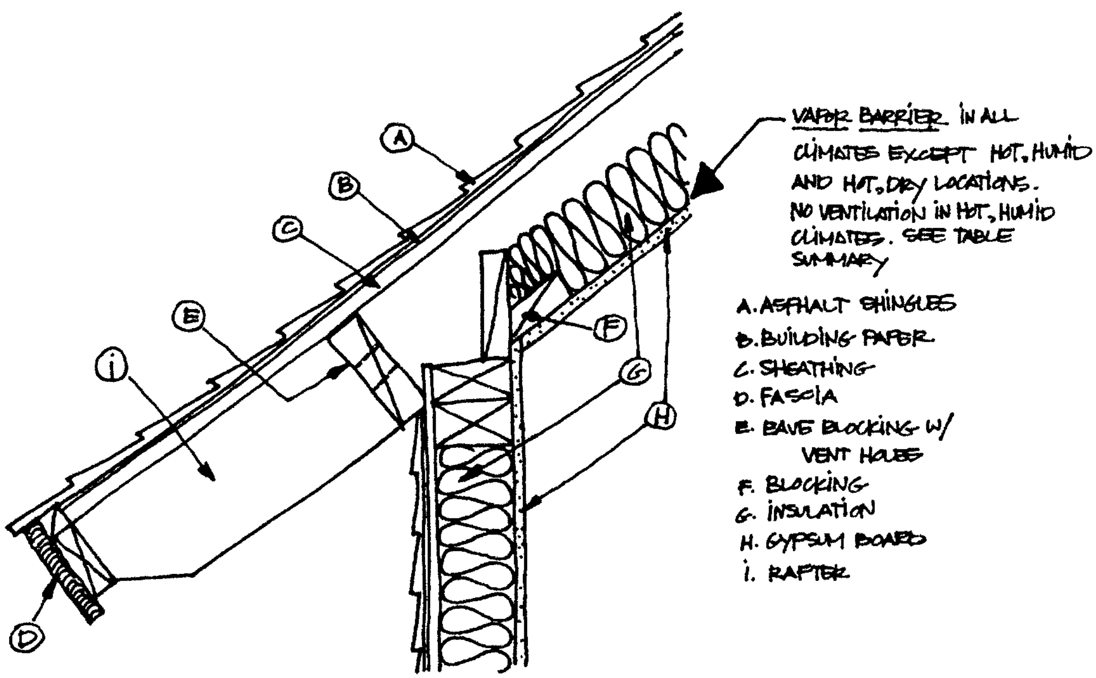


Figure 2.9, Adapted standard cathedral ceiling detail from Ramsey and Sleeper (1992).

2.5 Summary

While the specifics are not provided for all situations that can be encountered in the building systems of the United States, several common and general details are discussed with areas of inclusion and exclusion noted. The standards as defined by the American Society of Testing Materials (ASTM), and the codes of the Council of American Building Officials, CABO: One and Two Family Dwelling Code, 1995 Edition, Fourth Printing, and International Code Council, International Residential Code: For One and Two Family Dwellings provide the industry with the recommendations and requirements of when, where, and if to utilize these materials in our structures. Some, but not all, of the code recommendations make sense in light of the literature that was reviewed, but where the codes do not make sense recommendations are provided.

The author has come to the conclusion that regardless of the literature that has been reviewed, the subject of vapor barriers remains a greatly misunderstood and confusing building material. Builders ridicule the literature and construct out of experience and not what either the literature or simple calculations reveal. It is the opinion of the author that vapor barriers should be used in heating climates at all locations within the structure's foundation, wall, and roof assemblies. The implementation of a vapor barrier should be included within the foundation and wall assemblies of all structures in a cooling climate, but that the specific application in the roof remains one area that depends upon the specific, detailed structure's design but specific recommendations have been made in the roofing section for several roof types.

While this report's specific aim is to clarify and determine when, where, and if to utilize a vapor barrier in the mixed climate area, the topic remains quite variable and specific depending upon the design, materials utilized, and orientation of the structure. A vapor barrier is recommended for the foundation and roof assembly for all structures in this climate, but the when and where to utilize a vapor barrier within the wall remains less clear. The literature states that a vapor barrier is not necessary within the wall in a mixed climate. The literature also states that the principles of flow-through design are to be utilized in this area, and for this reason an air barrier should not be incorporated into the design. The flow of air through the wall is the driving agent of moisture into and out of the wall assembly depending upon the season. The principle of flow-through design allows wetting during one season and drying during the opposite that should effectively handle moisture within the cavity. The flow-through principles should effectively control moisture in the mixed climate without the needed incorporation of a vapor barrier into the wall system. It is the opinion of the author that a vapor barrier is not needed for the mixed climate. A vapor barrier may be used in the wall section, and should be placed in the same position as in the cooling climate wall. The benefits of utilizing a vapor barrier in the mixed climate do not outweigh those for not using one. The added cost, without benefits, should help make the decision easier not to use a vapor barrier in a mixed climate.

2.6 References Cited

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3.0 WUFI Data Results Summary

3.1 Background of Software Program, Initial Assumptions, and Limitations

WUFI, Wärme-und Feuchteransport Instationär (Transient Heat and Moisture Transport), is a program that was developed as part of two student dissertations at German Universities in 1994 and 1995. The Oak Ridge National Laboratory is the point of contact for the software in the United States. The WUFI software program that was used for the data interpretation was the "Student Version" software. The WUFI program is an effective testing tool for the analysis of Thermal Conductivity, Diffusion Resistance, Liquid Transport, Total Water Content in the construction and in the individual components, Solar Radiation calculations, Air Temperatures changes, and the Relative Humidity level changes at various component locations within the wall system. The WUFI program does allow the user to model the different directional conditions that the wall system would be exposed to by allowing the user to select the direction of the wall, such as North, South, East, and West. The user can run the test wall through each different direction to see the directional impact that the building systems will experience.

The "Student Version" software program has several data and program output limitations. The program does provide the end user with the information necessary to calculate the dew point but stops short of plotting the dew point for the respective data runs. In addition, the software evaluates the effects of diffusion through materials but does not consider the effects of air movement through the wall system. As the title states, the point of interest is in "Transient Heat and Moisture Transport," but the moisture transport is limited to transport through diffusion, which as the literature review stated, is the mechanism that transports the least amount of moisture through the building assembly. The inputs for the wall systems that could be tested were limited to being able to test vertical wall assemblies only, so no roof or foundation systems could be tested or evaluated. The library of components that the "Student Version" of the software offered was extremely limited, and the only assemblies discussed in the previous sections that could be tested were for a wood (spruce) siding model and a brick veneer model.

The major assumption that was made with regards to the WUFI data is that air movement, not vapor diffusion, is the major transport method to be dealt with in our wall systems. The WUFI student version software program evaluates the effects of vapor diffusion through the wall system but does not address the effects of air movement, which the literature reviewed stated is the predominant means of transporting vapor through the building systems. Air penetrates the building system and allows vapor to enter the building materials through the joints between materials, at the corners, through inlets and outlets, at the top plate, and sill plates. Once air enters the wall system, the potential for condensation to form within the cavity is created at the next coldest location once the dew point has been attained. The wall section evaluations that the WUFI program performs are similar to those discussed in Section 1.3.2.1.2, Perfect Barriers, and as such do not consider any of the effects that the quality of the construction detail has on our

buildings. The construction detail that is done correctly and has no openings for air to move through the wall components would behave in this manner, but that level of construction cannot be attained throughout the entire building and therefore air movement should still be considered. As such, the effects of air movement through the wall system were not modeled or considered discussion of the WUFI results that follow in the next few sections, but these effects still need to be considered.

The data result interpretations were made utilizing the assumption that air movement, not vapor diffusion, transports the majority of moisture vapor in our wall cavities. The results that were obtained from the WUFI software indicate this assumption to be true. The results with regard to air transported moisture vapor remains unproven/untested in this report's result section that follows. This assumption was validated by the WUFI results because the relative humidity levels, due to vapor diffusion, rarely rose high enough at the expected dew point locations to reach the dew point and create liquid condensate. The monitor positions 2 and 3 within the modeled walls are the theoretical points within the wall cavity where condensate (caused by the attainment of the dew point on the next cold surface) would be expected to form within the wall. The theory of where condensate typically occurs within the wall systems helped determine the likely points within the wall cavity to establish and monitor the relative humidity levels.

The software program also has several output limitations that were observed during the test runs and the subsequent data interpretation process. The outputs for the "Student Version" of the program were quite limited and would only allow the end user to view preprogrammed outputs that were in graphical form and did not allow any tabular data outputs or other forms of customization. Sample manual dew point calculations utilizing the psychrometric charts from Stein and Reynolds, Mechanical and Electrical Equipment for Buildings: 8th Edition, utilizing the relative humidity and temperature readings that WUFI generated have been accomplished and may be seen found in Figures 3.2 - 3.7 at the end of this section (Stein and Reynolds, 1992).

3.2 Model Development and Data Interpretations

Once the software program had been experimented with and the program's limitations were better understood, the code system, Table 3.1, was developed to maintain control over the numerous data samples that were taken. The purpose of utilizing the WUFI program became to test the findings from the literature review that vapor moved by air transported mechanisms is the predominant issue within the wall cavity. Diffusion through the wall materials is not the primary concern because the amount of vapor moved by diffusion is negligible when compared to air transport.

Table 3.1, WUFI File Data Key	
1-2-3-4-5-6-7.pdf	
Block 1	What is the wall section? 1 – Brick and 2 – Spruce
Block 2	VB – Vapor Barrier or NVB – No Vapor Barrier
Block 3	Where is structure located? R – Roanoke, M – Minneapolis, and NO – New Orleans
Block 4	What month the data was run for? 1 – January, 4 – April, 7 – July, and 10 - October
Block 5	What is interior climate control? AC – Air Condition and NAC – No Air Condition
Block 6	Data plot number (1 or 2)
Block 7	Where is the vapor barrier location? 1 – New Orleans and 2 - Minneapolis
For example, a 1-VB-R-4-AC-1-2 means that the .PDF file is for a Brick veneer structure, with a vapor barrier, in Roanoke, during April, in an air conditioned space, that the plot was the first one, and that the vapor barrier location was in the same location that the vapor barrier would occupy in Minneapolis (i.e., between the gypsum board and the insulation).	

The tests run, using the WUFI program, created 112 data samples for the two exterior wall cover systems. The tests were conducted only for the months of January, April, July, and October with the belief that these tests would provide enough data to show how the "vapor barrier"/"no vapor barrier" assemblies behaved to test the conclusions that were drawn in the previous sections for a heating climate (Minneapolis), a mixed climate (Roanoke), and a cooling climate (New Orleans) with respect to vapor diffusion. The wall section that was utilized in the 112 tests is as diagrammed in Figure 3.1.

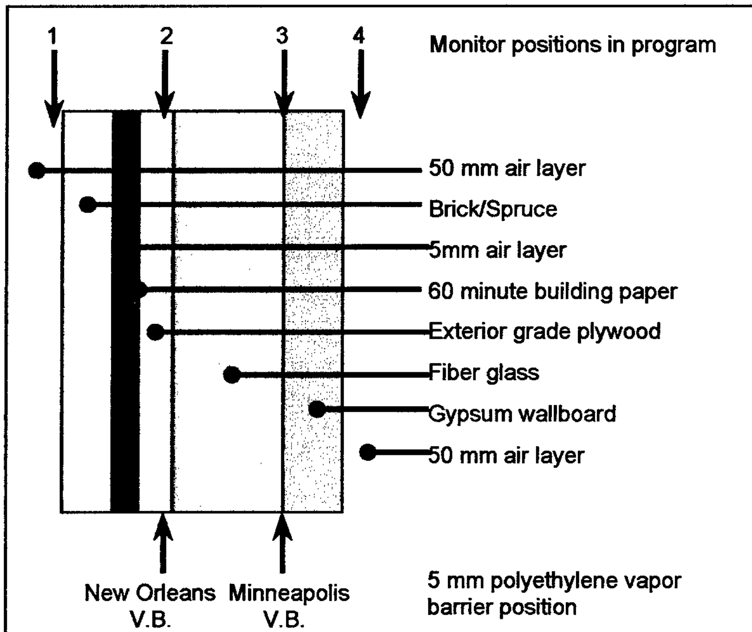


Figure 3.1, WUFI wall section utilized in the tests

The program only allowed for the monitoring of four positions per test run, and the exterior and interior positions were default positions established in the program. The other two selected positions were placed within the wall section at the most likely accumulation points for vapor/condensation once the dew point is reached within the cavity.

The use of a five-millimeter polyethylene vapor barrier was selected since this vapor barrier presented the wall section to the vapor retarding material with the lowest permeability and least capacity to store vapor. The other alternative for the vapor barrier was to utilize a "smart vapor barrier" which is a wax or asphalt impregnated building paper that retains water in some seasons and dries during the opposite one. The "smart vapor barrier" was not used due to its capacity to retain water and subsequently dry. The two positions for the vapor barriers within the wall section are the two expected vapor barrier installation points utilized in the construction industry and in the literature reviewed. The New Orleans positioned vapor barrier was placed on the exterior or warm side of the insulation due to the high temperatures and high levels of humidity to be experienced from the exterior and the use of air conditioning in the interior. The Minneapolis positioned vapor barrier was placed on the interior side of the insulation to account for the cold exterior temperatures and the high use of heating systems by the occupants for the majority of months in the year.

3.2.1 New Orleans Data Results

The test results for the New Orleans wall sections without a vapor barrier, both brick and spruce models, had nearly identical results utilizing the WUFI software. The only noted variations within the wall sections occurred within the monitored position 2, and the relative humidity levels did not vary more than approximately ±2% relative humidity. The relative humidity levels did not change significantly during the course of a one-month test run. The noted changes within the wall section can be attributed to the diffusion characteristics of the materials, and since the exterior materials are relatively the same, the amount of infiltration within the two different cavities appears to be similar. The relative humidity levels at both monitor positions 2 and 3 were similar when compared to the same positions in the vapor barrier and no vapor barrier models.

The test results for the New Orleans wall sections with vapor barrier were nearly identical to the no vapor barrier models when compared during the month of January, when the exterior relative humidity levels were the lowest for the year. The test results during the month of April, when compared to the same month's model without a vapor barrier, were nearly identical. The relative humidity levels rose quite significantly when compared to the conditions during January, but remain consistent with the no vapor barrier model during the same time period. The relative humidity levels at both monitor positions 2 and 3 were similar when compared to the same positions in the vapor barrier and no vapor barrier models.

The July test results for the New Orleans wall section with a vapor barrier compared to the section without a vapor barrier showed very similar results during the first 20 days of the test run. The exterior relative humidity levels were extremely high when compared to the two previous

months' test run data. The data that was monitored at monitor position 2 showed a decline in the relative humidity levels in the vapor barrier wall section. The deviation at the 20-day period is approximately 5% lower when compared to the no vapor barrier model. The respective deviations at the 25- and 30-day periods are approximately 5% lower at each of the periods and show a significant drop in the relative humidity. These data results correlate to less opportunity for condensate to form, and thus less opportunity for mold and fungi propagation. The monitor position 3 remains identical for both vapor barrier and no vapor barrier systems with regards to relative humidity.

The October test results show relative humidity levels that are higher than both the January and April test runs, but significantly less than those experienced and tested during the July run. The data obtained from monitored position 2 within the wall section shows a slight decline at the 25- and 30-day periods. The drop in relative humidity levels for the vapor barrier wall when compared to the no vapor barrier wall is approximately 5% less per 5-day period. The monitor position 3 relative humidity levels remain identical for both of the tested systems.

Table 3.2, New Orleans summary of relative humidity data results from WUFI when compared to the no vapor barrier model results

New Orleans	VB placement	
	Monitor 2	Monitor 3
January – Spruce Model	---	---
April – Spruce Model	---	---
July – Spruce Model	↓	---
October – Spruce Model	↓	---

The New Orleans test data graphs can be found in Appendix 1 at the end of the report.

3.2.2 Minneapolis Data Results

The test results for the Minneapolis brick and spruce wall sections with no vapor barrier showed very slight to no deviation utilizing the WUFI software. The deviations noted were all seen at monitor position 3 within the wall section with only one noted change occurring at monitor position 2. The first relative humidity deviation at monitor position 3 occurred in January around the 20-day point and was approximately 5% higher in the spruce model. The relative humidity levels in the spruce model at the 25-day point was approximately 3% higher, and the 30-day period saw a rise of approximately 5%. The April test run did not reveal any relative humidity level changes at monitor position 3. The July test run revealed relative humidity level changes at monitor position 2 beginning at day 10. The change at day 10 showed an increase in relative humidity on the spruce model compared to the brick model of approximately 3%. The relative humidity level

changes for the 15-, 20-, 25-, and 30-day periods showed a rise of approximately 5% per 5-day period in the spruce model. The rise in the relative humidity levels during July in the spruce model is very likely to be attributable to the moisture storage and diffusion characteristics of the spruce. The monitor position 3 in July does not show any significant change between the two models. The October test result data does not show any significant changes in either the monitor 2 or 3 positions. The test run data for the spruce and brick wall sections with vapor barrier show nearly identical test results. The slight deviations were noted, but the change was approximately ±1% relative humidity at only a very few data points and do not appear significant enough to specifically draw attention to those points.

The January test data, both spruce and brick models, comparing the no vapor barrier to the vapor barrier models reveals that the relative humidity level rises approximately 2% in the no vapor barrier model at monitor position 2 at the 10-day period. The relative humidity level increase continues for the 15-, 20-, 25-, and 30-day periods at monitor position 2 with the increases being approximately 2%, 4%, 5%, and 8%, respectively. The monitor position 3 data results show that the relative humidity levels are significantly lower for the no vapor barrier models at the beginning of the test run. At the end of a 5-day period, the relative humidity level for the vapor barrier wall at monitor position 3 is approximately 15% higher. The relative humidity levels for the 10-, 15-, 20-, 25-, and 30-day periods show increases of approximately 20%, 25%, 15%, 10%, and 25%, respectively.

The April test data, for both the spruce and brick veneer models, comparing the no vapor barrier to the vapor barrier models reveals that the relative humidity level rises approximately 1% in the no vapor barrier model at monitor position 2 at the 10-day period. The relative humidity rise continues for the 15-, 20-, 25-, and 30-day periods at monitor position 2 with the increases being approximately 2%, 3%, 5%, and 5% respectively. The monitor position 3 data results show that the relative humidity levels are lower for the no vapor barrier models at the beginning of the test run. At the end of a 5-day period, the relative humidity level for the vapor barrier model at monitor position 3 is approximately 12% higher. The relative humidity levels for the 10-, 15-, 20-, 25-, and 30-day periods show increases of approximately 10%, 5%, 8%, 2%, and 5%, respectively.

The July test data, for both the spruce and brick models, comparing the no vapor barrier to the vapor barrier models reveals that the relative humidity level decreases approximately 1% in the no vapor barrier model at monitor position 2 at the 5-day period. The relative humidity level decrease continues for the 10-, 15-, 20-, 25-, and 30-day periods at monitor position 2 with the decreases being approximately 5%, 10%, 12%, 15%, and 20%, respectively. The relative

humidity levels for monitor position 3 in the no vapor barrier and vapor barrier wall does not reveal any significant deviations between the test data.

The October test data for both the vapor barrier and no vapor barrier models reveal identical relative humidity levels for both wall systems at monitor position 2 in the cavity. The data for monitor position 3 shows a general increase in the relative humidity levels for the no vapor barrier model beginning at the 5-day period with a noted increase of approximately 4%. The increases for the 10-, 15-, 20-, 25-, and 30-day periods are approximately 1%, 1%, 10%, 8%, and 3%, respectively.

Table 3.3, Minneapolis summary of relative humidity data results from WUFI when compared to the no vapor barrier model results

Minneapolis – Brick and Spruce models	VB placement	
	Monitor 2	Monitor 3
January	↑	↓
April	↑	↓
July	↓	---
October	---	↑

The actual test run data for the Minneapolis wall sections may be found in Appendix 2 at the end of the report.

3.2.3 Roanoke Data Results

The test results for the Roanoke brick and spruce wall sections without a vapor barrier had only very slight to no deviations noted utilizing the WUFI software in the months of January and April for monitor positions 2 and 3. However, the July data results show a substantial relative humidity level decrease in the brick model compared to the spruce siding model beginning at day 5 at monitor position 2. The relative humidity level at monitor position 2 decreases for the 5-, 10-, 15-, 20-, 25-, and 30-day periods are approximately 2%, 4%, 10%, 12%, 15%, and 18%, respectively. The relative humidity levels for the monitor position 3 during July were identical for the vapor barrier and no vapor barrier models. The relative humidity levels for position monitors 2 and 3 during October were identical for the vapor barrier and no vapor barrier models.

The test results for the brick wall sections, vapor barrier and no vapor barrier, for the month of January at monitor position 2 show identical relative humidity levels for the vapor barrier located in the New Orleans vapor barrier placement. The monitor position 2 relative humidity levels for the Minneapolis vapor barrier placement are identical until the 15-day period, which then shows a decrease in relative humidity of approximately 1%. The 20-, 25-, and 30-day data periods show a decrease in relative humidity of 2%, 4%, and 5%, respectively. The relative humidity levels for the New Orleans placed vapor barrier at the monitor position 3 is identical to the no vapor barrier

wall. The Minneapolis placed vapor barrier at the monitor position 3 shows a fairly significant increase in relative humidity levels when compared to the no vapor barrier wall system. The relative humidity increase at the 5-, 10-, 15-, 20-, 25-, and 30-day periods is approximately 5%, 10%, 8%, 12%, 10%, and 15%, respectively.

The April data results for the brick wall at monitor position 2 remains nearly identical for the New Orleans placed vapor barrier as in the no vapor barrier model. The Minneapolis placed vapor barrier model shows a relative humidity decrease at the monitor position 2 beginning at the 10-day period of approximately 1%. The decreases for the 15-, 20-, 25-, and 30-day periods is approximately 3%, 4%, 5%, and 4%, respectively at monitor position 2. The monitor position 3 for the New Orleans placed vapor barrier remains identical to the no vapor barrier model. The monitor position 3 for the Minneapolis placed vapor barrier shows mixed levels of increase and decrease starting at the 5-day period. The data shows slight decrease in relative humidity in the vapor barrier model at the 5-day period, an increase of approximately 5% in the vapor barrier model at each of the 10- and 15-day periods. The model shows the relative humidity level rising approximately 4% higher in the no vapor barrier wall compared to the vapor barrier model at the 20-day period, and this rises to approximately 10% for the 25-day period. The vapor barrier model's relative humidity level rises to approximately 4% higher than the no vapor barrier model.

The July data for the brick wall at monitor position 2 remains identical for the New Orleans vapor barrier position and the no vapor barrier walls. The monitor position 2 for the Minneapolis placed vapor barrier remains significantly higher than the no vapor barrier wall. The relative humidity levels at the 5-, 10-, 15-, 20-, 25-, and 30-day periods are increased approximately 3%, 5%, 10%, 15%, 20%, and 23% when compared to the no vapor barrier system. The monitor position 3 reading for the New Orleans placed vapor barrier is identical to the no vapor barrier wall. The monitor position 3 reading for the Minneapolis placed vapor barrier is significantly lower in the vapor barrier wall during the 5-, 10-, 15-, and 20-day periods at which point the data results parallel the no vapor barrier wall. The relative humidity levels for the 5-, 10-, 15-, and 20-day periods are approximately 15%, 5%, 4%, and 3% lower in the Minneapolis placed vapor barrier wall.

The October test data for the brick wall at monitor position 2 shows a slight increase in relative humidity for the New Orleans and Minneapolis placed vapor barrier walls in comparison to the no vapor barrier wall. The increase in relative humidity in the New Orleans and Minneapolis placed vapor barrier walls is seen at the 10-, 15-, 20-, 25-, and 30-day periods. The increases in relative humidity are approximately 2%, 4%, 4%, 4%, and 4% higher in the New Orleans and Minneapolis placed vapor barrier walls compared to the no vapor barrier wall in monitor position 2. The

monitor position 3 in the New Orleans positioned vapor barrier wall is identical to the no vapor barrier wall. The monitor position 3 in the Minneapolis positioned vapor barrier wall shows a fluctuation in relative humidity levels nearly identical to the levels previously discussed in the April data section.

The test results for the spruce wall sections, vapor barrier and no vapor barrier, for the month of January at monitor position 2 shows a slight relative humidity level increase of approximately 2% at each of the 5 day periods for the vapor barrier located in the New Orleans vapor barrier placement. The data for monitor position 2 in the Minneapolis placed vapor barrier wall shows a slight decrease of 2% at each of the 5-day periods. The Minneapolis placed vapor barrier at the monitor 3 position shows a fairly significant increase in relative humidity levels when compared to the no vapor barrier wall system. The relative humidity increase at the 5-, 10-, 15-, 20-, 25-, and 30-day periods is approximately 5%, 10%, 8%, 12%, 10%, and 15%, respectively, which is nearly identical to the conditions experienced in the brick wall mentioned above.

The April data results for the spruce wall at monitor position 2 remains nearly identical for the New Orleans and Minneapolis placed vapor barriers as the no vapor barrier models. The monitor position 3 for the New Orleans placed vapor barrier remains identical to the no vapor barrier model. The monitor position 3 for the Minneapolis placed vapor barrier shows mixed levels of increase and decrease starting at the 5-day period. The data shows slight increase in relative humidity in the vapor barrier model at the 5-day period, and an increase of approximately 5% in the vapor barrier model at each of the 10- and 15-day periods. The model shows the relative humidity level rising approximately 5% higher in the no vapor barrier wall compared to the vapor barrier model at the 20-day period, and this rises to approximately 10% for the 25-day period. The vapor barrier model's relative humidity level increases approximately 2% more than the no vapor barrier model.

The July data results for the New Orleans placed vapor barrier wall at monitor position 2 shows a decrease in the relative humidity levels compared to the no vapor barrier wall beginning at the 10-day period. The relative humidity levels for the 10-, 15-, 20-, 25-, and 30-day periods are approximately 2%, 5%, 8%, 10%, and 12% lower in the New Orleans placed vapor barrier wall compared to the no vapor barrier wall system. The conditions for the Minneapolis placed vapor barrier wall are approximately 4%, 5%, 7%, 10%, and 13% higher in the vapor barrier wall when compared to the no vapor barrier wall at the 10-, 15-, 20-, 25-, and 30-day periods, respectively. The monitor position 3 in the New Orleans placed vapor barrier wall has identical relative humidity levels when compared to the no vapor barrier wall. The Minneapolis placed vapor barrier wall shows a decline in relative humidity levels when compared to the no vapor barrier wall at monitor

position 3. The relative humidity levels are approximately 8%, 5%, 4%, 3%, 2%, and 2% higher in the no vapor barrier wall compared to the Minneapolis placed vapor barrier wall.

The October data for the spruce wall at the monitor position 2 remains identical for the New Orleans vapor barrier position and the no vapor barrier walls. The relative humidity levels for the 10-, 15-, 20-, 25-, and 30-day periods are approximately 2%, 4%, 5%, 5%, and 5% higher in the Minneapolis placed vapor barrier wall compared to the no vapor barrier wall system. The monitor position 3 for the New Orleans placed vapor barrier remains identical to the no vapor barrier model. The monitor position 3 for the Minneapolis placed vapor barrier shows mixed levels of increase and decrease starting at the 5-day period. The data shows a slight decrease in relative humidity in the vapor barrier model at the 5-day period, and an increase of approximately 5% in the no vapor barrier model at each the 10- and 15-day periods. The model shows the relative humidity level rising approximately 3% higher in the vapor barrier wall compared to the no vapor barrier model at the 20-day period. The relative humidity level in the no vapor barrier model is approximately 4% higher for the 25-day period compared to vapor barrier model, and the no vapor barrier model's relative humidity level is approximately 2% higher than the vapor barrier model at the 30-day period.

Table 3.4, Roanoke summary of relative humidity level data results from WUFI when compared to the no vapor barrier model results

Roanoke	New Orleans VB placement		Minneapolis VB placement	
	Monitor 2	Monitor 3	Monitor 2	Monitor 3
January – Spruce Model	↑	—	↓	↑↑
April – Spruce Model	—	—	—	↑
July – Spruce Model	↓	—	↑	↓
October – Spruce Model	—	—	↑	↑↓
January – Brick Model	—	—	↓	↑↑
April – Brick Model	—	—	↓	↑↓
July – Brick Model	—	—	↑	↓
October – Brick Model	↑	—	↑	↑↑

** NOTE: A "↑↑" means significant increase and a "↑↓" means mixed increase and decrease.

The actual test run data for the Roanoke wall sections may be found in Appendix 3 at the end of the report.

3.3 Summary

The WUFI results that have been discussed only discuss the impact that vapor diffusion has on these wall systems and does not consider the effects that air movement has on the same wall system. The results obtained from the WUFI tests indicate that the effects of vapor diffusion on the wall system materials as tested are consistent with the recommendations made in the literature reviewed.

Following the assumption that air moves more moisture vapor than diffusion, the topic of air carried moisture vapor remains the greatest enemy of the wall system in our residences. The principle of preventing air-transported moisture has created the need to discuss quality control in residential construction. The most effective means to prevent or retard the flow of air through a wall system is to ensure that when the wall is constructed that the air barrier and any penetrations (such as vents, outlets, etc.) are correctly and carefully detailed and installed to minimize air movement into the wall system at these locations. It is the opinion of the author that if careful and thorough attention to these details the effects felt in our wall systems due to moisture vapor penetration will be lower. The assumption that air moves far more moisture vapor that diffusion influenced the test data results because the WUFI test data results indicate that diffusion is not the primary means to be concerned with within our wall systems. The WUFI results indicate that the dew point was not reached within the wall cavity at the expected dew point locations using the few dew point calculations that were made in Figures 3.2 – 3.7.

The WUFI tests allowed the following conclusions for the New Orleans wall test runs. The positioning of the vapor barrier does not affect the manner in which the wall behaves significantly because the absorption characteristics of the wall materials do not allow significant quantities of moisture to diffuse through the wall materials. The effects of air movement and the transport capabilities through this mechanism are still believed to be the dominant means of vapor movement, but it remains unproven due to the limitations of the WUFI software program. The test results for the New Orleans test walls show the necessity of installing a vapor barrier in the hot, humid climate if diffusion is the only concern. The minor relative humidity decreases seen in the New Orleans test walls only considering the diffusion through the material would lead to the conclusion that a vapor barrier is definitely needed in the wall system when air movement is added to the system.

The conclusions that can be drawn from the Minneapolis data test on the brick and spruce wall sections are that a vapor barrier should be included in the wall section to handle the effects of diffusion through the materials in this climate. The literature reviewed stated that the vapor barrier was needed in this climate and the WUFI test data provide clear validation. The effects of

diffusion in this climate would justify inclusion of a vapor barrier in the wall system without even needing to consider the effects of air movement. The author further believes that if the wall section could be modeled for air movement through the system, the differences in relative humidity levels in the no vapor barrier and vapor barrier models would continue to increase, and the inclusion of a vapor barrier would remain justified in the wall section. It is also still believed that with the incorporation of air flow the relative humidity level increase on the exterior sections of the wall would be reduced.

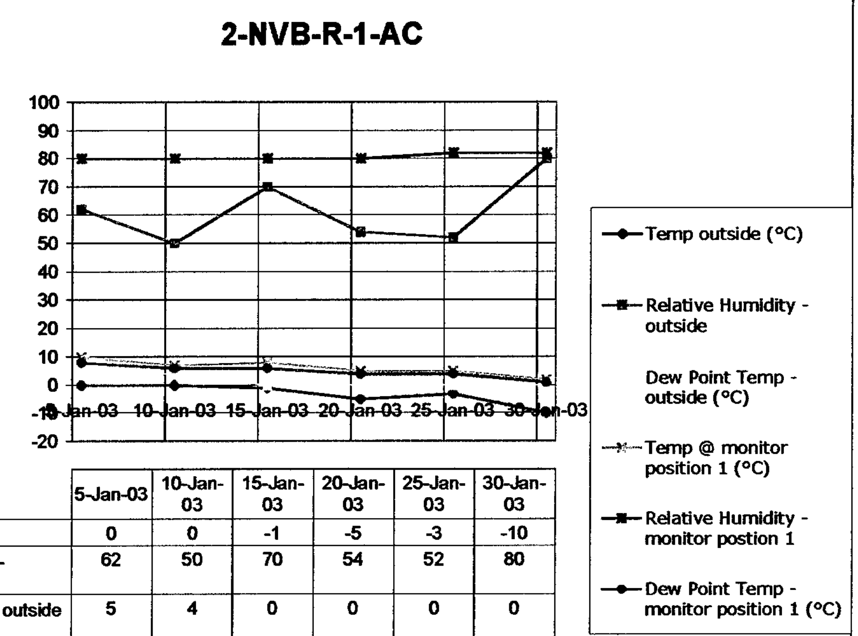
The conclusions that can be drawn from the Roanoke data test runs on the brick and spruce wall sections show that a brick siding should be selected over spruce siding in a no vapor barrier wall system. The brick veneer wall would facilitate lower relative humidity levels within the wall cavity due to less vapor diffusion through the material when compared to spruce siding. For the spruce and brick walls in Roanoke, the recommendation is to not place a vapor barrier in the wall system because the attained results are similar to the results experienced by placing a vapor barrier on the exterior side (similar to New Orleans) of the insulation. The placement of the vapor barrier on the interior side (similar to Minneapolis) of the insulation shows varying changes in the relative humidity levels on both the interior and exterior wall surfaces. The vapor barrier placement in this mixed climate location is not recommended. The WUFI program results show that with the diffusion characteristics in this mixed climate utilizing a spruce and brick wall, it is not necessary to incorporate a vapor barrier, which is in-line with the literature reviewed.

The effect of air movement remains the primary factor in determining whether or not to utilize a vapor barrier in the construction of a wall system. The overall lessons learned utilizing the WUFI software, considering vapor diffusion through the materials within the wall system are:

1. A vapor barrier <u>is</u> necessary in cooling climates to combat the effects of diffusion.
2. A vapor barrier <u>is</u> necessary in heating climates to combat the effects of diffusion.
3. A vapor barrier <u>is not</u> necessary in mixed climates to address diffusion through the wall.

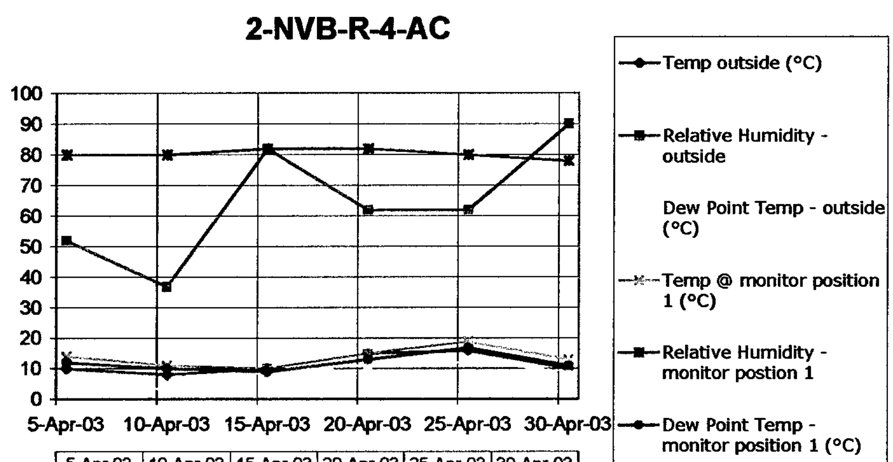
Builders ridicule the literature and construct out of experience rather than what either the literature or wall analysis calculations reveal. In summary, it is the opinion of the author that vapor barriers should be used in heating climates at all locations within the structure's foundation, wall, and roof assemblies. The implementation of a vapor barrier should be included within the foundation and wall assemblies of all structures in a cooling climate, but the specific application in the roof remains one area that depends upon the specific, detailed structure design. A vapor barrier is recommended for the foundation and roof assembly for all structures in the mixed climate, but the when and where to utilize one within the wall system remains less clear. The literature states that a vapor barrier is not necessary within the wall in this climate. The principles

of flow-through design are to be utilized in this climatic area according to the literature reviewed. The flow of air through the wall is the primary driving agent of moisture into and out of the wall assembly depending upon what season the structure is in currently. The principle of flow-through design allows wetting during one season and drying during the opposite so that moisture within the cavity attains equilibrium during the course of the year.



	5-Jan-03	10-Jan-03	15-Jan-03	20-Jan-03	25-Jan-03	30-Jan-03
Temp outside (°C)	0	0	-1	-5	-3	-10
Relative Humidity - outside	62	50	70	54	52	80
Dew Point Temp - outside (°C)	5	4	0	0	0	0
Temp @ monitor position 1 (°C)	10	7	8	5	5	2
Relative Humidity - monitor postion 1	80	80	80	80	82	82
Dew Point Temp - monitor position 1 (°C)	8	6	6	4	4	1

Figure 3.2, Spruce Siding, without vapor barrier, in Roanoke, in January with air conditioning.
Outside temperature, relative humidity – outside, Temperature at monitor position 1, and relative humidity – monitor position 1 obtained from WUFI (2003). Dew Point data obtained from Stein B. and Reynolds. J. (1992).



	5-Apr-03	10-Apr-03	15-Apr-03	20-Apr-03	25-Apr-03	30-Apr-03
Temp outside (°C)	10	8	10	15	16	10
Relative Humidity - outside	52	37	82	62	62	90
Dew Point Temp - outside (°C)	6	3	9	11	12	9
Temp @ monitor position 1 (°C)	14	11	10	15	19	13
Relative Humidity - monitor postion 1	80	80	82	82	80	78
Dew Point Temp - monitor position 1 (°C)	12	10	9	13	17	11

Figure 3.3, Spruce Siding, without vapor barrier, in Roanoke, in April with air conditioning.
Outside temperature, relative humidity – outside, Temperature at monitor position 1, and relative humidity – monitor position 1 obtained from WUFI (2003). Dew Point data obtained from Stein B. and Reynolds, J. (1992).

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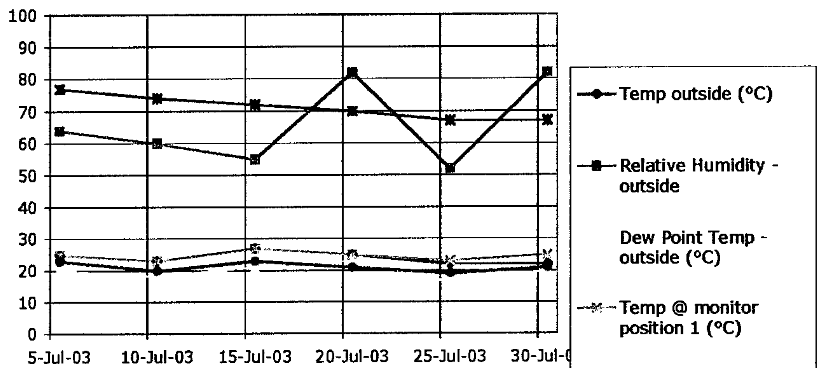

	5-Jul-03	10-Jul-03	15-Jul-03	20-Jul-03	25-Jul-03	30-Jul-03
Temp outside (°C)	25	23	27	25	22	22
Relative Humidity - outside	64	60	55	82	52	82
Dew Point Temp - outside (°C)	20	18	21	23	16	20
Temp @ monitor position 1 (°C)	25	23	27	25	23	25
Relative Humidity - monitor postion 1	77	74	72	70	67	67
Dew Point Temp - monitor position 1 (°C)	23	20	23	21	19	21

Figure 3.4, Spruce Siding, without vapor barrier, in Roanoke, in July with air conditioning.
Outside temperature, relative humidity – outside, Temperature at monitor position 1, and relative humidity – monitor position 1 obtained from WUFI (2003). Dew Point data obtained from Stein B. and Reynolds, J. (1992).

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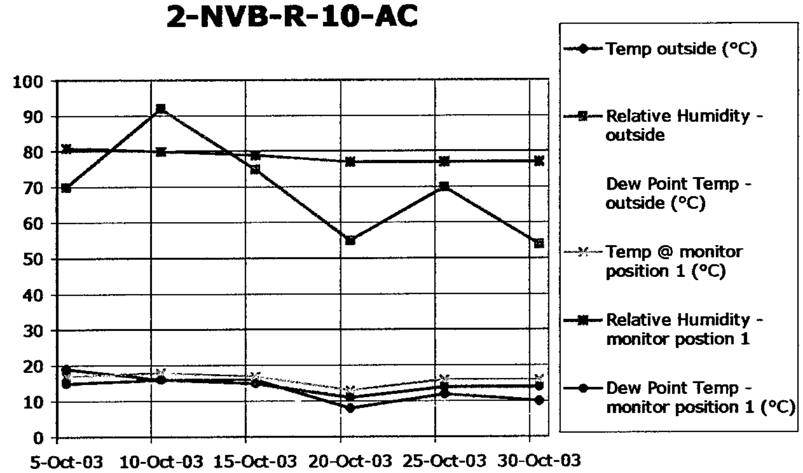
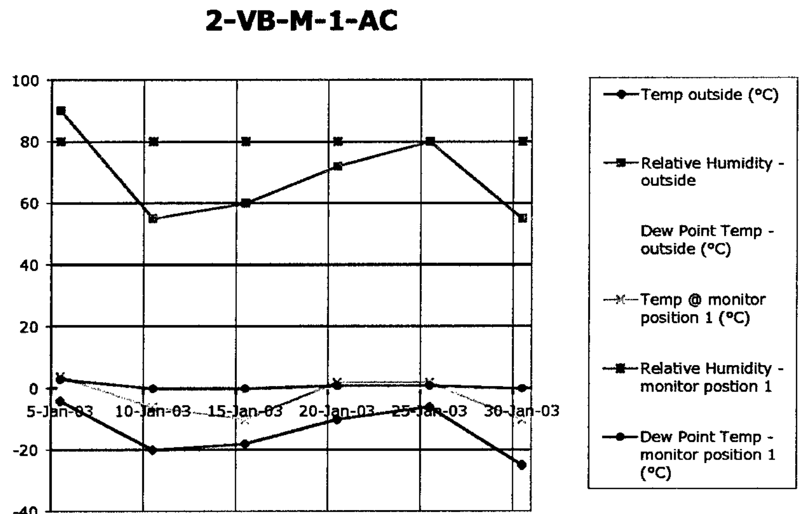


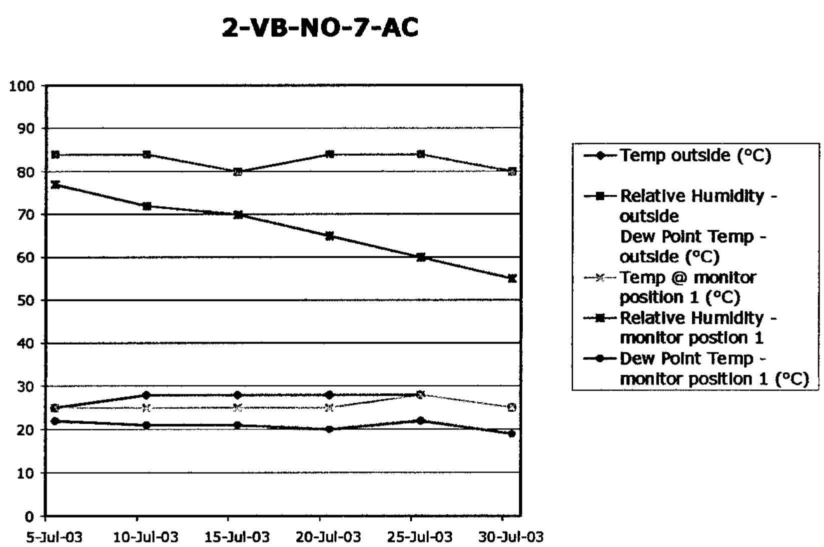
	5-Oct-03	10-Oct-03	15-Oct-03	20-Oct-03	25-Oct-03	30-Oct-03
Temp outside (°C)	19	16	16	8	12	10
Relative Humidity - outside	70	92	75	55	70	54
Dew Point Temp - outside (°C)	16	15	14	5	9	6
Temp @ monitor position 1 (°C)	17	18	17	13	16	16
Relative Humidity - monitor postion 1	81	80	79	77	77	77
Dew Point Temp - monitor position 1 (°C)	15	16	15	11	14	14

Figure 3.5, Spruce Siding, without vapor barrier, in Roanoke, in October with air conditioning.
Outside temperature, relative humidity – outside, Temperature at monitor position 1, and relative humidity – monitor position 1 obtained from WUFI (2003). Dew Point data obtained from Stein B. and Reynolds, J. (1992).



	5-Jan-03	10-Jan-03	15-Jan-03	20-Jan-03	25-Jan-03	30-Jan-03
Temp outside (°C)	-4	-20	-18	-10	-6	-25
Relative Humidity - outside	90	55	60	72	80	55
Dew Point Temp - outside (°C)	0	0	0	0	0	0
Temp @ monitor position 1 (°C)	4	-6	-10	2	2	-10
Relative Humidity - monitor postion 1	80	80	80	80	80	80
Dew Point Temp - monitor position 1 (°C)	3	0	0	1	1	0

Figure 3.6, Spruce Siding, with vapor barrier, in Minneapolis, in January with air conditioning.
Outside temperature, relative humidity – outside, Temperature at monitor position 1, and relative humidity – monitor position 1 obtained from WUFI (2003). Dew Point data obtained from Stein B. and Reynolds, J. (1992).



	5-Jul-03	10-Jul-03	15-Jul-03	20-Jul-03	25-Jul-03	30-Jul-03
Temp outside (°C)	25	28	28	28	28	25
Relative Humidity - outside	84	84	80	84	84	80
Dew Point Temp - outside (°C)	23	26	25	26	26	23
Temp @ monitor position 1 (°C)	25	25	25	25	28	25
Relative Humidity - monitor postion 1	77	72	70	65	60	55
Dew Point Temp - monitor position 1 (°C)	22	21	21	20	22	19

Figure 3.7, Spruce Siding, with vapor barrier, in New Orleans, in July with air conditioning.
Outside temperature, relative humidity – outside, Temperature at monitor position 1, and relative humidity – monitor position 1 obtained from WUFI (2003). Dew Point data obtained from Stein B. and Reynolds, J. (1992).

3.4 References Cited

Stein B. and Reynolds, J. (1992). Mechanical and Electrical Equipment for Buildings: 8th Edition. John Wiley and Sons, Inc.; New York; 1627 p.

WUFI. (2003). *WUFI: Wärme-und Feuchteransport instationär (Transient Heat and Moisture Transport), Educational Software Program.* Oak Ridge National Laboratory; Oak Ridge TN; obtained from www.ornl.gov/ORNL/BTC/moisture/, accessed on 1 Sep 03.

4.0 Summary and Conclusions

4.1 Summary

Moisture dissipation from within a wall is directly related to both the air movement and vapor diffusion through the structure's wall assembly materials (Carll, 2000). The rampant use of vapor barriers in residential construction has in many instances created redundant vapor barriers within the wall cavities that trap moisture and water. Even if the vapor barriers are not redundant, the vapor barrier's placement is oftentimes in the wrong location, creating as many problems as redundancy. A vapor barrier's location should be carefully designed and specifically applied in relation to the wall design, climatic conditions, and directional orientation (North, South, East, or West) of the wall. In order to control moisture, designers and builders must look holistically at the indoor and outdoor atmospheric conditions of the building system's design to create the appropriate foundation, walls, and roof sections for the building assembly (Carll, 2000). The recommended placement of a vapor barrier should not be universal even within similar climatic regions. The specific, individual wall system design and climatic conditions should be studied and incorporated when determining whether or not to use a vapor barrier.

The major problem cited by independent residential builders in new housing construction is moisture, primarily rot, decay, and the growth of molds and fungi. Condensation and moisture related problems were first recognized and investigated in a 1923 Forest Products Laboratory survey of dwellings due to early exterior paint failure on residential houses (U.S. Forest Service, 1949). It has more recently been reported, "with the exception of structural errors, 90% of building construction problems are associated with water" and the harmful effects related to its penetration into our structures (Trechsel, Achenbach, and Launey, 1982). Current building codes and property standards also contribute to this problem because the methods being employed are prescriptive rather than performance oriented and these codes have tried to create a universal approach for construction rather than looking holistically at the wall assembly components (Trechsel, Achenbach, and Launey, 1982 and Sherwood and Moody, 1989).

The recommendations that follow may or may not be in line with the requirements made under the codes and property standards currently in use. The recommendations are broken down into common areas of interest within our structures, foundation, walls, and roofs. Each section is a summary of what the report states in more detail.

4.2 Detail Conclusions and Specifics for Foundations, Walls, and Roofs

4.2.1 Foundations

The foundation vapor barrier design is straightforward and consistent for heating, cooling, and mixed climates. A vapor barrier should be included in all climates as a ground cover under slab-on-grade and in crawl spaces. The accumulation of moisture through the foundation/support elements (slab, basement, crawl space, etc.) is the primary point of entry into residential

construction assemblies (Suprenant, 1994). The incorporation of vapor barriers in the foundation design is only going to be as effective as the drainage mechanisms facilitate. Designing proper drainage includes not only collecting the water, but also effectively moving the water out and away from the structure so that the water does not accumulate and then migrate back up and into the wall system. Two typical design details for the slab-on-grade and a crawl space may be seen in Figures 4.1 and 4.2.

The placement of the sub-slab vapor barrier will perform a dual role in the structure's moisture protection. The first role is to break capillary movement of moisture upward and into the structure's assembly (Lstiburek and Carmody, 1991). The sub-slab vapor barrier's role is to break capillarity, and it provides the building with its first preventative measure in dealing with moisture and minimizing the potentially harmful effects within the structure. Special care should be taken to ensure that the vapor barrier's integrity is maintained since it is also fulfilling the role of an air barrier.

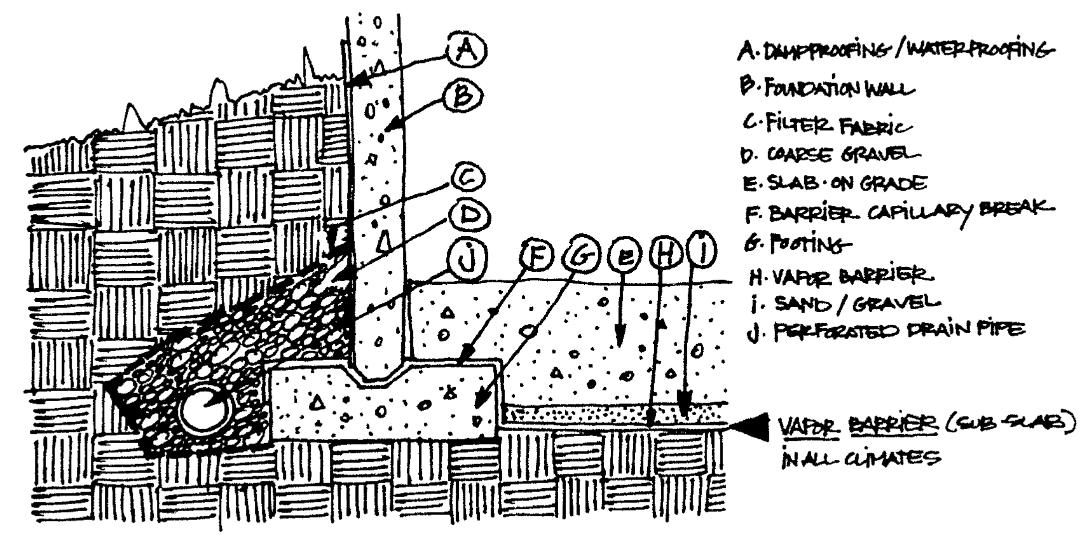


Figure 4.1, Adapted standard slab-on-grade and basement detail from Ramsey and Sleeper (1992).

The second role of the sub-slab vapor barrier is to help prevent moisture migration through the porous concrete (Suprenant, 1994). The vapor barrier material for this application may include sheet polyethylene, dampproofing material, multiple layers of roofing paper, or EPDM sheeting. All joints should be lapped at least six inches, and the vapor barrier material should be as impervious as possible to any breaks, punctures, or other such penetrations (Suprenant, 1994). The role of the vapor barrier in this particular application should be designed and constructed in a similar manner as an air barrier within the wall system. The vapor barrier should be placed on top of, and in direct contact with, the compacted subgrade material. Then, on top of the vapor barrier and below the concrete slab, a three-inch thick layer of sand or varied sizes of gravel should be

applied and lightly compacted (Suprenant, 1994). Gravel is recommended over sand because gravel is less easily displaced during the placement of the concrete slab and provides a consistently more uniform surface for the slab's placement (Suprenant, 1994). A discussion with a residential house builder stated that this layer is seldom incorporated because of the significant cost and the perceived benefits of incorporation do not outweigh the increased cost of installation (Vinson, 2003). Special care and oversight should be taken during the concrete placement phase since the vapor barrier's effectiveness is proportional to the integrity of the barrier membrane below (JLC Staff, 1993).

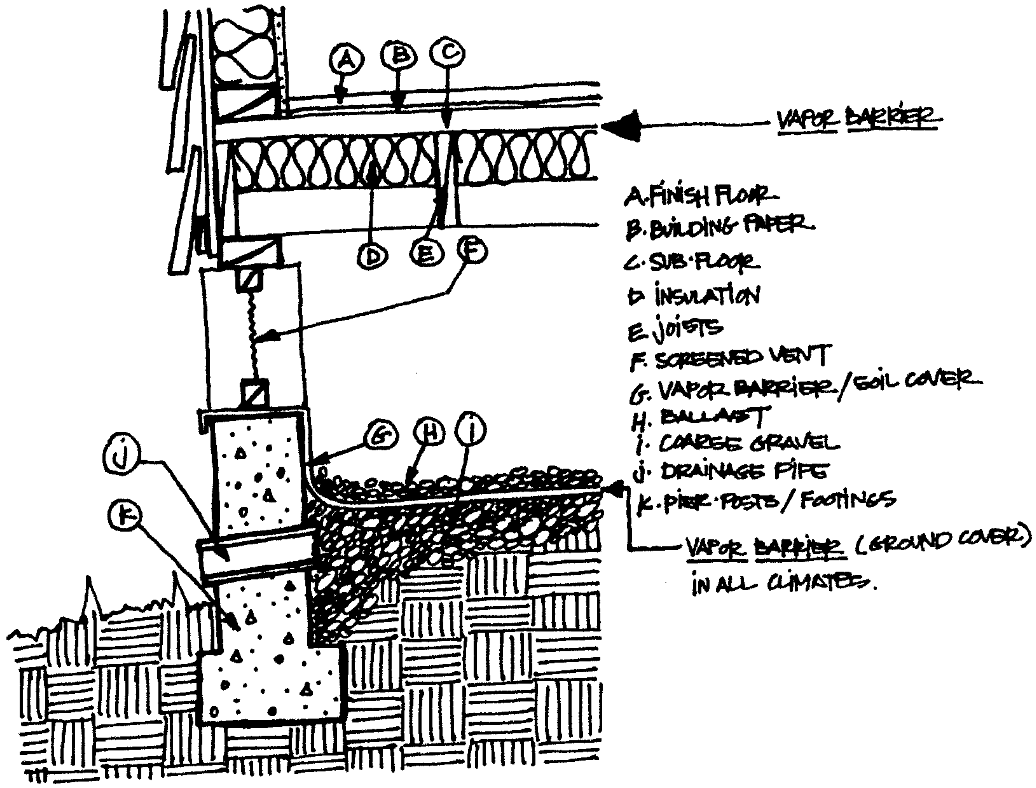


Figure 4.2, Adapted standard crawl-space detail from FPL (1949) and Ramsey and Sleeper

The requirements, as outlined in the CABO and ICC codes, make recommendations for the incorporation of vapor barriers in the on-grade, sub-slab section that are in line and follow the recommendations and guidance discovered during the review of literature.

4.2.2 Walls

The climate where the residence wall is to be located, in conjunction with the composition of the wall components, strictly define how, where, and if a vapor barrier should be included in the design. As previously discussed, the directional orientation of the wall system also plays a significant role in determining when to place a vapor barrier within the wall system. The internal

wall temperatures vary significantly depending on if the wall is exposed to climatic conditions on the north, south, east or west sides of the structure. The wall assembly temperatures and thermal mass effects are greatly impacted by the directional orientation. The examples selected do not represent all known housing solutions, merely the most popularly used solutions in the residential construction industry today. The wall system assembly descriptions with the associated component R-values and material thicknesses used in this paper's investigation may be found in Table 4.1.

Table 4.1 – Wall system components, R-value, and materials thicknesses

Wall System Model & Components	*R-value*	*Material Thickness*
Wood siding model:		
- Outside air	.17 in winter & .25 in summer	N/A
- Wood siding, beveled, lapped (back primed)	.81	.5"
- Furring strips or similar air gap	1.35	.25"
- Building paper/ housewrap, permeable	.06	Negligible
- 1/2" Douglas fir plywood	.62	.5
- Unfaced rolled batt-insulation	11	3.5"
- Gypsum board with paint	.56	5/8"
- Inside air	.68	N/A
Brick veneer model (light wood frame):		
- Outside air	.17 in winter & .25 in summer	N/A
- Face brick	.2	2.66"
- Air space	1.35	.25"
- Building paper/ housewrap, permeable	.06	Negligible
- 1/2" Douglas fir plywood	.62	.5"
- Unfaced rolled batt-insulation	11	3.5"
- Gypsum board with paint	.56	5/8"
- Inside air	.68	N/A
Plaster veneer model (on light wood frame):		
- Outside air	.17 in winter & .25 in summer	N/A
- Stucco	.1	.5"
- Durarok®	.26	.5"
- Building paper/ housewrap, permeable	.06	Negligible
- 1/2" Douglas fir plywood	.62	.5"
- Unfaced rolled batt-insulation	11	3.5"
- Gypsum board with paint	.56	5/8"
- Inside air	.68	N/A
Concrete shell/Holistic house model:		
- Outside air	.17 in winter & .25 in summer	N/A
- Sealed concrete	.95	2"
- Styropor insulation	38.25	8.5"
- Gypsum board with primer coat and latex paint	.56	5/8"
- Inside air	.68	N/A
***All R-values were obtained from Stein and Reynolds (1992), pages 136-143, with the exceptions of Styropor and Durarok® that were obtained from manufacturer's specifications.		

The conclusions developed regarding where to install a vapor barrier in a cooling climate and a heating climate are in line with the information discovered during the literature review. The WUFI program results indicate the same conclusions as those discovered during the literature review. The vapor barrier should be installed on the warm-in-winter side of the insulation for both climates' wall system design solutions (heating climate: the vapor barrier is placed on the interior face of the insulation; and the cooling climate: the vapor barrier should be placed on the exterior face of the insulation). The positioning of the vapor barriers within the brick veneer and spruce siding model wall cavities for both heating and cooling climates are diagrammed in Figure 4.3.

The positioning of the vapor barrier in these locations follows the literature reviewed, and matches the vapor diffusion results obtained from the WUFI Student Version software-modeling program.

The potential for redundancy still exists in these structures. The effects of the redundancy (caused by multiple layers of latex paint) in a cooling climate's structure are expected to be worse than those in the heating climate. The placement of the intentional vapor barrier on the exterior side of the insulation in a cooling climate and the inclusion of the inadvertent vapor barrier on the interior side of the gypsum board will create a potential vapor trap in the insulation and gypsum board components of the cooling climate's wall assembly. The effect of redundancy caused by paint in the heating climate creates a vapor trap inside of the gypsum board, so it may be concluded that the effects of vapor accumulation will be significantly minimized.

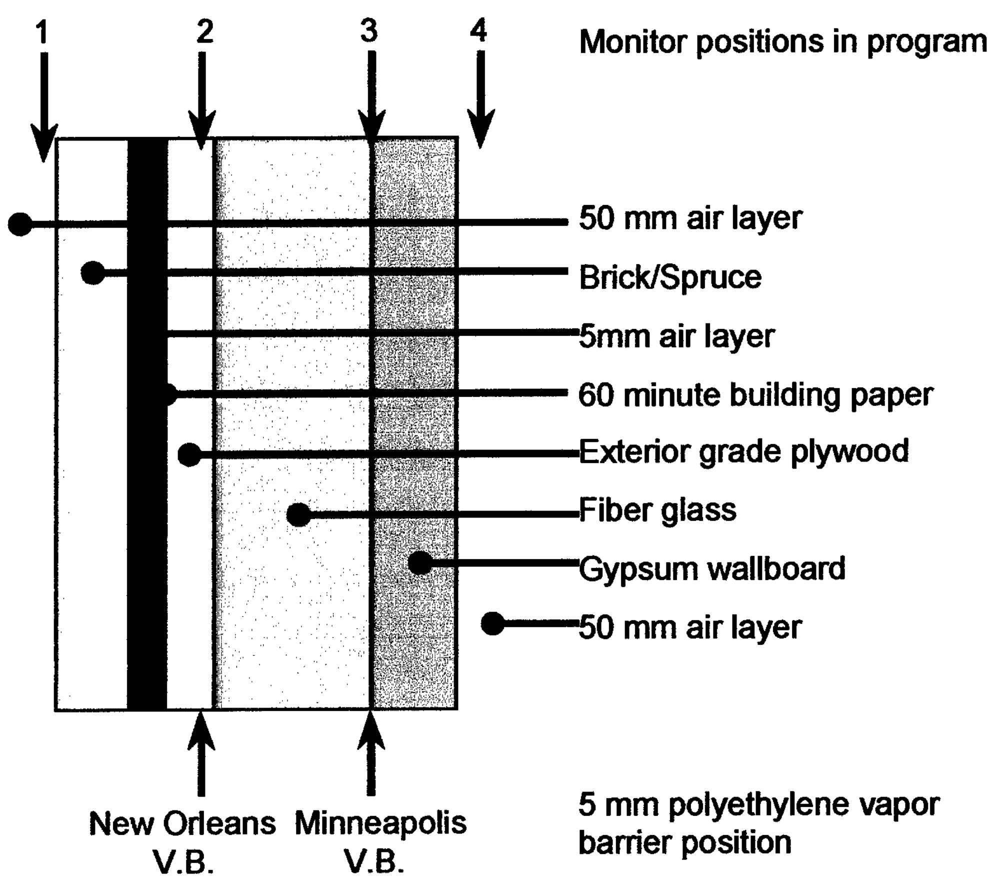


Figure 4.3 – Typical Brick Veneer and Spruce Siding wall section composition and the associated vapor barrier location within each section, drawing by author

In a mild, more temperate climate a vapor barrier is not necessary. For example, for the brick veneer wall it is recommended that no vapor barrier be included because the vapor diffusion difference varies only slightly when compared to the same wall with a vapor barrier. A vapor

barrier may be utilized, in the same location as that in a cooling climate, but the added expense of a vapor barrier should dictate its exclusion since no reductions in relative humidity were observed in the WUFI data results for vapor diffusion. Proper ventilation and clear weep holes in this wall cavity and climate must exist because once water enters the cavity it should have both a means to exit and a means to dry. If the water is not allowed to exit once it enters the cavity, the water will seek equilibrium within the space and migrate across other materials. The spruce siding wall assembly has the same recommendations as those for the brick veneer wall. A plaster veneer wall should be avoided in this climate. The plaster wall system's component composition (Durarok® and plywood) on the interior of the plaster coat behaves like a vapor retarder for vapor diffusion through the wall system. It is recommended that this assembly be avoided in mixed and heating climates. A concrete shell model that contains a super insulated wall should not necessitate a vapor barrier.

4.2.3 Roofs

The use of a vapor barrier in the roof/ceiling components of the assembly is effective and recommended as a means of being able to reduce the ventilation requirements in this part of the assembly according to the codes. The specifics of utilizing, or not utilizing, a vapor barrier in this area of the assembly is dependent upon the climatic area of the structure, the design of the ceiling/roofing connection, and whether or not the roof is ventilated. All of these items must be considered in conjunction with one another and cannot be looked at or designed in isolation when making a determination for when to utilize a vapor barrier. Table 4.2 was developed to help explain the roof design recommendations contained in this report.

Table 4.2, Various Roofing V.B. Applications According to Climate

Roof Type	***Heating Climate***	***Mixed Climate***	***Cooling Climate***
Flat Roof	- V.B. may be installed between deck and insulation, if design calculations prove its necessity	- V.B. should be installed between deck and insulation, if the winter temps are as discussed in codes and design calculations necessitate incorporation	- V.B. not needed
Roof with Attic	- Super low permeance plastic sheet V.B. & air barrier designed between built-up roofing and insulation in 8000+ heating degree day climates - Higher permeance V.B. & air barrier designed between built-up roofing and insulation - Circulation/venting must be provided - Design calculations must be utilized to determine inclusion or exclusion	- Higher permeance V.B. & air barrier designed between built-up roofing and insulation - Circulation/venting must be provided - Design calculations must be utilized to determine inclusion or exclusion	- V.B. should not be used in this climate - Air circulation/venting sufficient in hot, dry environments - Air circulation/venting should be avoided due to high moisture concentrations in hot, humid environments - Air barrier designed to prevent air leakage

Roof Type	Heating Climate	Mixed Climate	Cooling Climate
Cathedral Ceiling	- V.B. installed below the insulation (in the interior side of insulation) - Ventilation at the eave and ridge vented - Design calculations must be utilized to determine inclusion or exclusion	- V.B. installed below the insulation (in the interior side of insulation) - Ventilation at the eave and ridge vented - Design calculations must be utilized to determine inclusion or exclusion	- V.B. not necessary - Ventilation requirements same as attic space and should occur at eave and ridge if ventilated
Note: The CABO and ICC codes state, "[n]et free cross-ventilation area may be reduced to 1 to 300 with installation of vapor retarder (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling."			

A great deal of debate is present in the literature that has been reviewed, and no firm consensus has been reached across all the material reviewed with regards to vapor barriers in the roof system. The only firm conclusion with regards to the inclusion or exclusion of vapor barriers in the roof design is to calculate the specific point where the dew point is reached within the roof system and place the vapor barrier on the next cold surface. The influence of air movement must be considered, as well as the potential for drying through air movement to the interior or exterior of the roofing system materials. The designer must also be cognizant of the fact that if a vapor barrier is included and the roof develops a leak, the vapor barrier could behave as a vapor trap and cause the system to retain the water by not allowing it to escape.

The codes state that the "[n]et free cross-ventilation area may be reduced to 1 to 300 with installation of vapor barrier (material with a transmission rate not exceeding 1 perm) installed on the warm side of ceiling" (CABO, 1995 and ICC, 2000). The allowed reduction does not appear to make any sense for the climatic areas where roof ventilation is required. One of the purposes of roof ventilation is to allow the space to dry out should the space below the roof become wet. The ventilation reduction allowance under the codes would hamper drying through ventilation. The opinion of the author is that the codes allowed reduction in ventilation within the roof cavity is not recommended. The ventilation of the roof is necessary in effectively combating moisture accumulation in heating and mixed climates but not in cooling climates.

4.3 Summary of Lessons Learned

The following points are the most important and salient points discovered in the course of the literature reviewed in conjunction with the WUFI test results:

1. In a cold climate, a vapor barrier should be installed close to the interior (warm) side of the insulation.
2. In a hot, humid, tropical climate a vapor barrier should be placed on exterior (warm) side of the insulation.
3. In mild, more temperate climates a vapor barrier may or may not be necessary depending upon the specific wall materials. For example,

a. The brick veneer wall may or may not require a vapor barrier installed on the exterior side of the insulation. It is recommended that no vapor barrier be included because the vapor diffusion difference (with a vapor barrier placed on the exterior side of the insulation) is not too different when compared to the same wall without a vapor barrier. The added expense of a vapor barrier should dictate not including one in this design since no significant benefits were observed in the WUFI test data results. The incorporation of proper ventilation and weep holes in this wall cavity design is a necessity because once water penetrates the cavity it should have a means to exit and a means to dry.
b. A spruce siding wall has the same recommendations as those made with the brick veneer wall previously discussed.
c. A plaster veneer wall should be avoided in this climate. This exterior wall system's components (Durarok® and plywood) behave like a vapor retarder for diffusion through the wall system and as such should be avoided.
d. A concrete shell that is super insulated does not necessitate a vapor barrier.

4. A vapor barrier should only be used if needed, and the use should be based upon the specific wall system design, climate and orientation (North, South, East, or West) of the structure's location and specific wall design. The climatic differences experienced by the different directional orientations may dictate different applications of vapor barriers within the same structure, but the specifics should be calculated for each structure.
5. A vapor barrier in a basement should be implemented in the same manner and location as it was (was not) in the above-grade wall system.
6. A vapor barrier performs as a ground cover below the slab-on-grade and in crawl spaces. The vapor barrier's inclusion in these locations helps reduce moisture transport through capillary movement/suction from the soil up and into the structure's materials.
7. The vapor barrier does not have to be airtight, but should be installed with as few imperfections as possible to prevent the flow of air and vapor into the envelope. A rule of thumb when installing vapor barriers is "a vapor barrier that covers 90% of the surface is 90% effective" (JLC Staff, 1993).
8. Common wall cover applications act as vapor barriers [i.e., multiple layers of non-vapor retarding paint (latex), 3+ coats; and wallpaper (especially vinyl wall covering)].
9. Air moves far more moisture than diffusion through materials.
10. The building's wall cavity should <u>not</u> be ventilated in hot, humid (cooling) climates.
11. The building's wall cavity should be ventilated in temperate and cold (heating) climates.
12. An air barrier is needed and should be designed into all structures, regardless of climate.
13. Care should be taken when installing an air barrier because the air barrier is <u>only</u> as functional as the air barrier's material integrity (i.e., be free of cuts, tears, punctures, rips).

14. Ventilation requirements in the attic space or crawl space should not be reduced with the inclusion of a vapor barrier.
15. All walls are different and will behave differently depending upon climate, orientation, and how they are to be constructed.

The overall lessons learned utilizing the WUFI software considering only vapor diffusion through the materials within the wall system are:

1. A vapor barrier <u>is</u> necessary in cooling climates to combat the effects of vapor diffusion.
2. A vapor barrier <u>is</u> necessary in heating climates to combat the effects of vapor diffusion.
3. A vapor barrier <u>is not</u> necessary in mixed climates to address vapor diffusion through the wall system.

The effects of air transported vapor remains the primary factor in determining whether or not to utilize a vapor barrier in the construction of a wall system. The WUFI results show that the effects of vapor diffusion are in line with those recommendations discovered during the literature review. The effects of air movement within the cavity and across the materials remains unproven due to the limitations of the WUFI software.

The effect of air movement through the building materials remains the primary issue to be addressed in the building system design and construction. The design of the detail is a straightforward process that can be obtained from standard detail sources. How the detail is constructed should be the primary area of concern during construction. The air barrier should be installed with no penetrations, cuts, tears, and openings. The air barrier's integrity is critical if the wall components are to be kept dry and not subjected to the harmful effects associated with moisture penetration due to air movement. The air barrier's integrity should be checked prior to the subsequent building assembly layers installation. The vapor barrier's integrity, on the other hand, does not have to be as perfect if the air barrier has been installed correctly. If the vapor barrier only has to combat the effects of vapor diffusion through the materials, rather than the effects of air movement, then a vapor barrier with a few minor blemishes will perform its role correctly and efficiently. If the vapor barrier is to fulfill the dual role of vapor and air barrier then the rules for installing an air barrier apply.

The quality assurance and quality control process is critical during the construction of the air barrier and the sub-slab/ground cover vapor barrier installation. These barriers should be installed as imperviously as possible and their integrity should be carefully checked prior to subsequent work being placed on top of their respective surfaces. The effectiveness of the wall system air barriers and the sub-slab/ground cover vapor barriers are only as effective as they are continuous (JLC Staff Report, 1993). Any and all penetrations should be patched or sealed. The

QA/QC procedures during construction of these barriers are vital to the success of the wall assembly in the building as it combats moisture.

The directional orientation that the wall faces plays a significant role in the determination of whether or not to include a vapor barrier within the wall. The directional orientation of south and west facing structure walls will require different design parameters than walls facing the north and the east. The south and west facing walls face more effects from thermal mass and heat gain due to their particular directional orientation. These walls can be expected to maintain higher temperature readings than those on the north and east facing walls throughout the year and the dew point temperatures, and possibly the dew point location, within the wall may vary significantly compared to the same wall on the east and north faces of the structure.

Vapor barriers, listed in Table 4.3, are often times used redundantly or inadvertently because of the many potential materials that fulfill the vapor barrier role. Vapor barriers on new construction are often times an intentionally installed material. As a building is renovated and repaired, redundancy and inadvertent vapor barriers are often times created.

Table 4.3 – Vapor barrier definition and examples

Definition	*Examples*
A Vapor Barrier or Vapor Diffusion Retarder has been defined as a material to: 1.) "The control of water vapor diffusion to reduce the occurrence or intensity of condensation" (Straube, 2001) that is driven by diffusion, 2.) A vapor barrier may have imperfections and small cracks in its surface without greatly impairing the performance of the permeable vapor barrier (Straube, 2001), or 3.) As defined by building codes as anything with a permeability of 1 perm or less (Lstiburek, 2000)	- Polyethylene sheet membrane (Visquene) or film (varying thicknesses, 2-6 millimeters and in 3-20 foot rolls) sealed with manufacturer recommended caulk, sealants, and tapes - EPDM - Plastic sheeting - Rubber membranes - Glass - Aluminum foil - Sheet metal - Oil-based paint - Bitumen or wax impregnated kraft paper - Wall coverings and adhesives - Foil-faced insulating and non-insulating sheathings - Vapor retarder latex paint - 2 coats of acrylic latex paint top coating with premium latex primer - 3 coats of latex paint - Scrim (open-weave fabric like fiberglass fabric) - Hot, asphaltic rubberized membranes - Some insulations (elastomeric foam, cellular glass, foil faced isofoam) if sealed - Aluminum or paper faced fiberglass roll insulation - Foil backed wall board - Rigid insulation or foam-board insulation - 1/4 inch Douglas fir plywood with exterior glue - High-performance cross-laminated polyethylene (Information from Lstiburek, 2000; ICAA, 2002; Spence, 1998; Bordenaro, 1991; Maness, 1991; Lotz, 1998; Lstiburek and Carmody, 1991; Forest Products Lab, 1949; DoE, 2002)

For example, a common manner in which an inadvertent vapor barrier is created in a residence is when the occupants repaint a room. The structure's wall, when constructed, may have had a primer coat on the gypsum wallboard and then two coats of non-vapor retarding latex paint. When the occupants repaint their walls to up-date their home with two new of coats of latex paint, they have unintentionally created a vapor barrier on the interior side of the wall. The inclusion of

this vapor barrier either creates a vapor barrier where none previously existed or has now created a redundant vapor barrier because of one that was intentionally installed during construction. Unintentional vapor barriers are frequently incorporated into buildings and should be avoided when possible. Caution should be taken when renovating or updating residences/structures.

In conclusion, builders ridicule the literature and construct out of experience and not what either the literature or wall analysis calculations reveal. The different climate summaries and opinions of the author are as follows:

1. *Heating Climate*: Vapor barriers should be used in heating climates at all locations within the structure's foundation, wall, and roof assemblies.
2. *Cooling Climate*: The implementation of a vapor barrier should be included within the foundation and wall assemblies of all structures in a cooling climate, but the specific application in the roof remains one area that depends upon the specific, detailed structure design.
3. *Mixed Climate*: A vapor barrier is recommended for the foundation and roof assembly for all structures in the mixed climate, but the when and where to utilize one within the wall system remains less clear. The literature states that a vapor barrier is not necessary within the wall in this climate. The principles of flow-through design are to be utilized in this climatic area according to the literature reviewed. The flow of air through the wall is the primary driving agent of moisture into and out of the wall assembly depending upon what season the structure is in currently. The principle of flow-through design should be adhered to since it allows wetting during one season and drying during the opposite so that moisture within the cavity attains equilibrium across the wall section during the course of the year.

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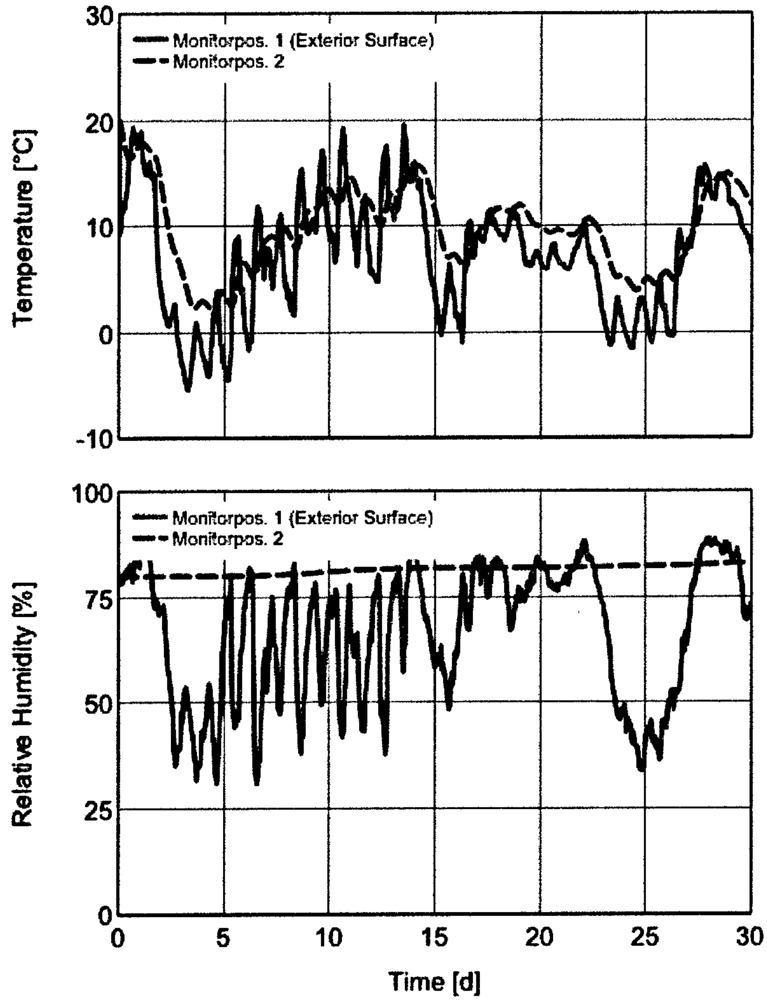
Appendix 1 – New Orleans Test Data



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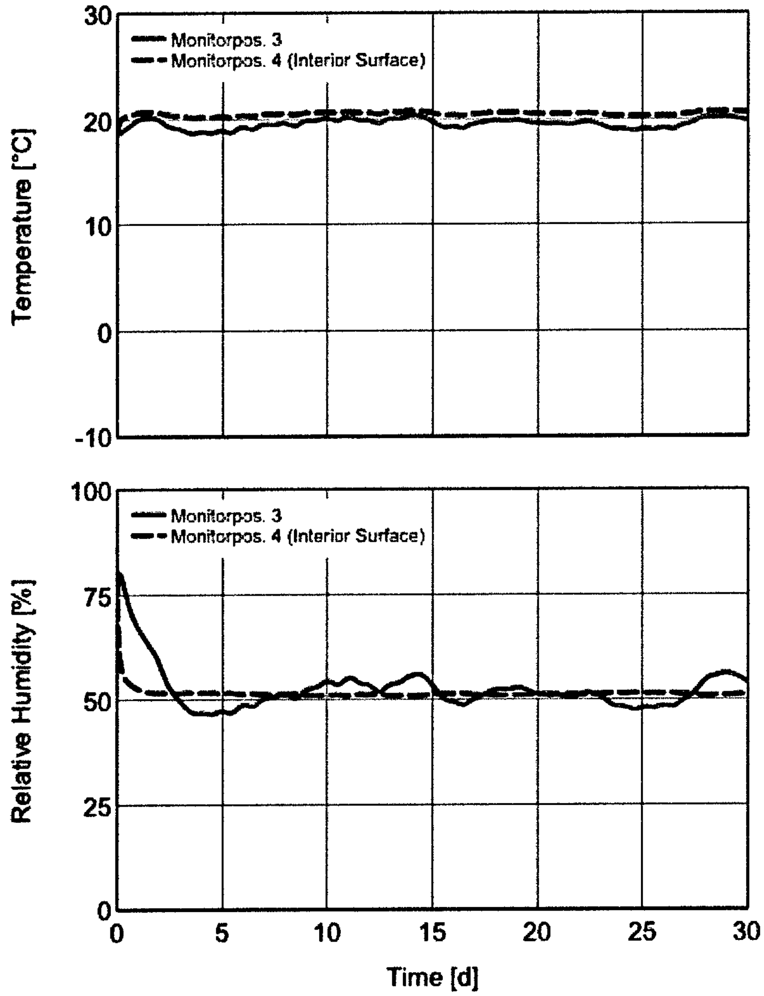
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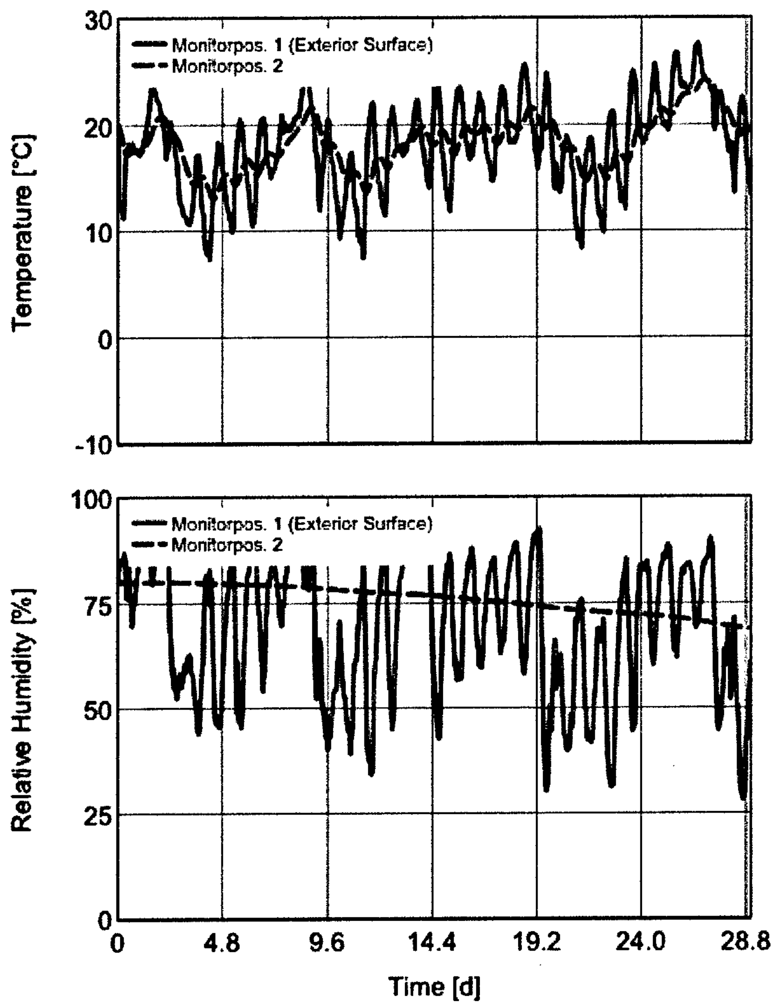

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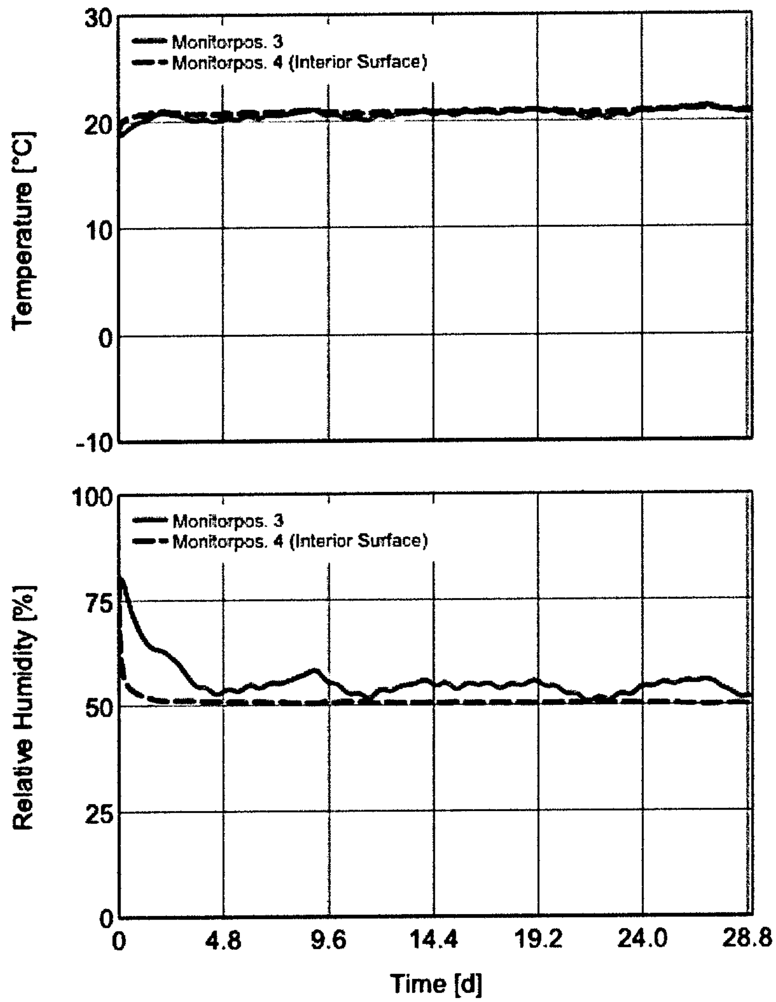
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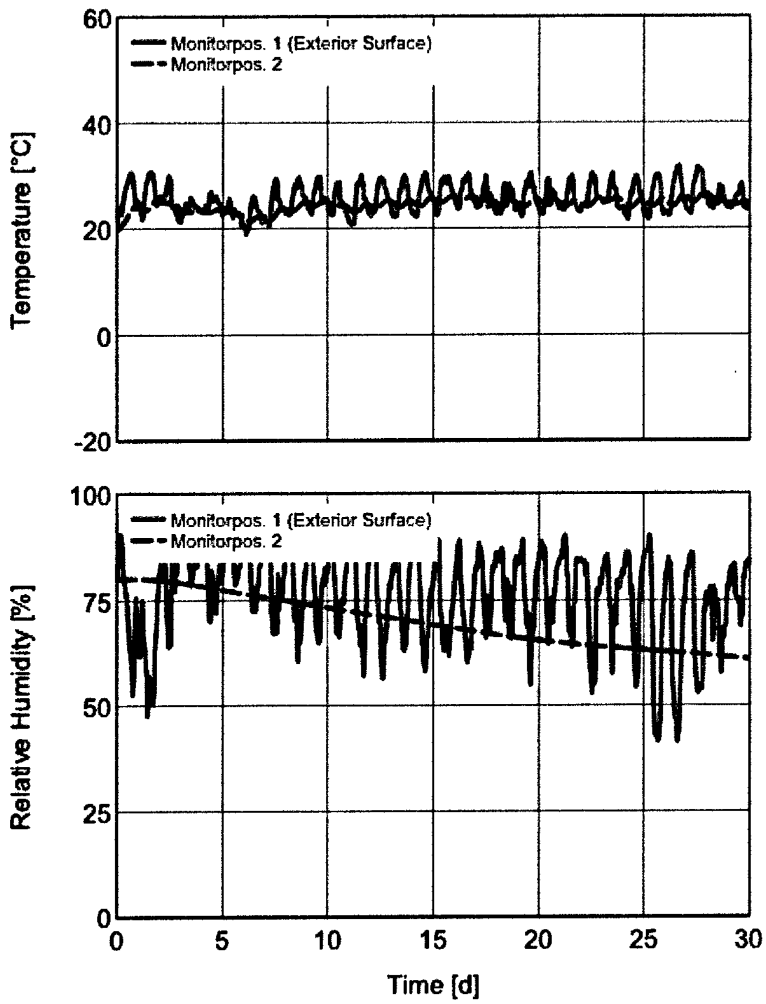

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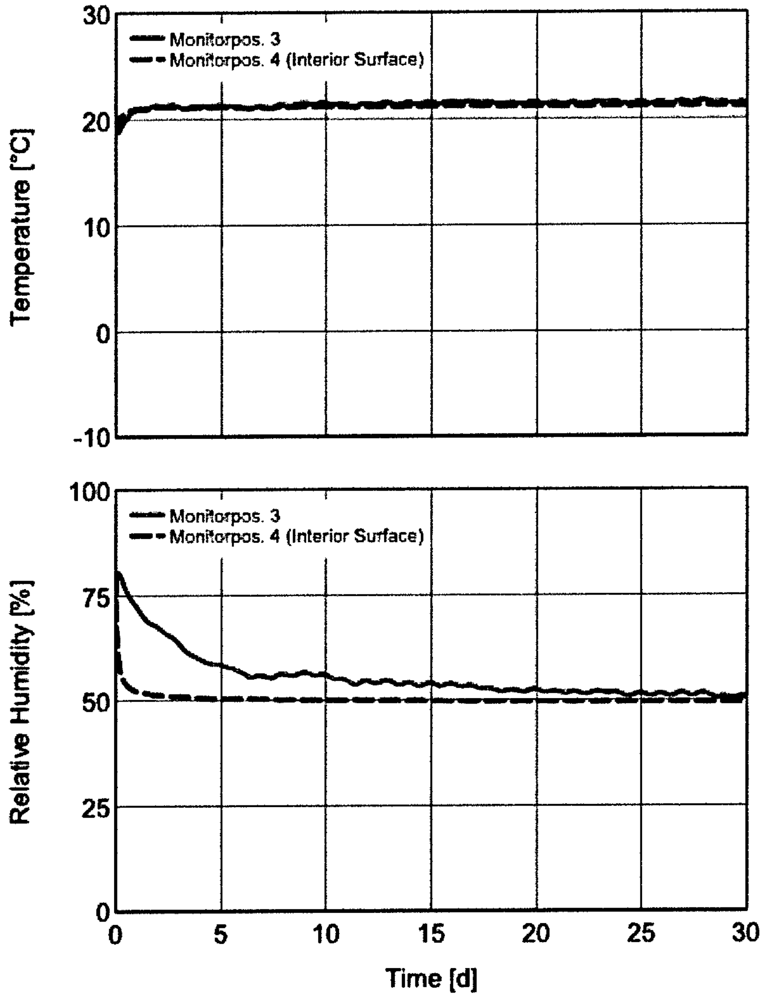

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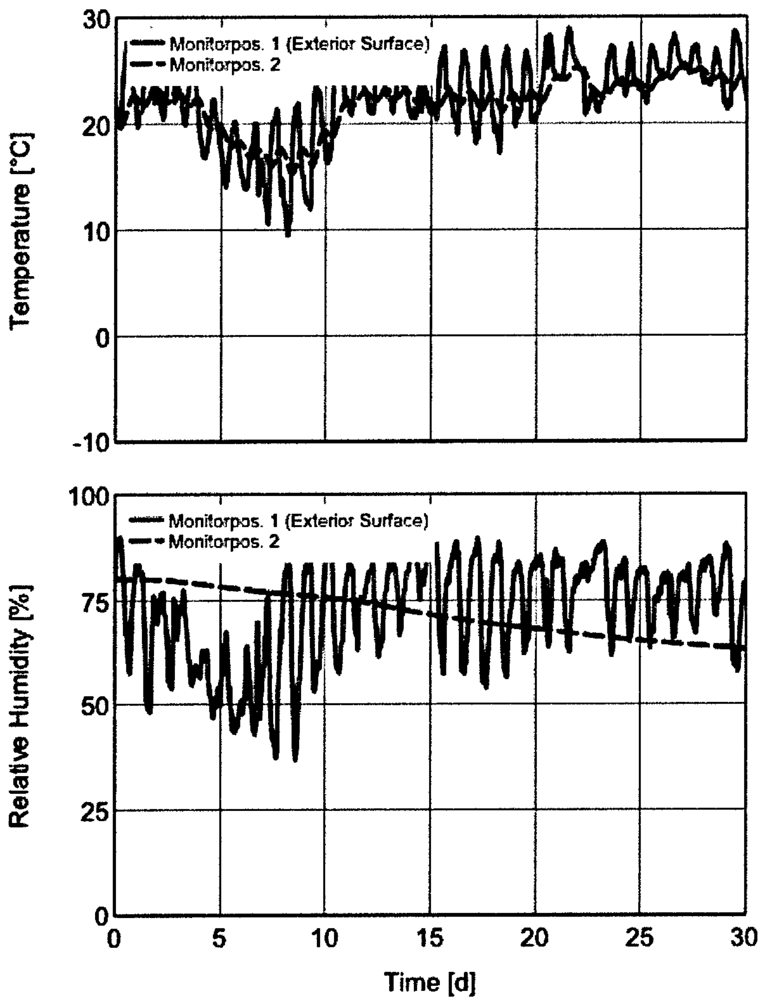
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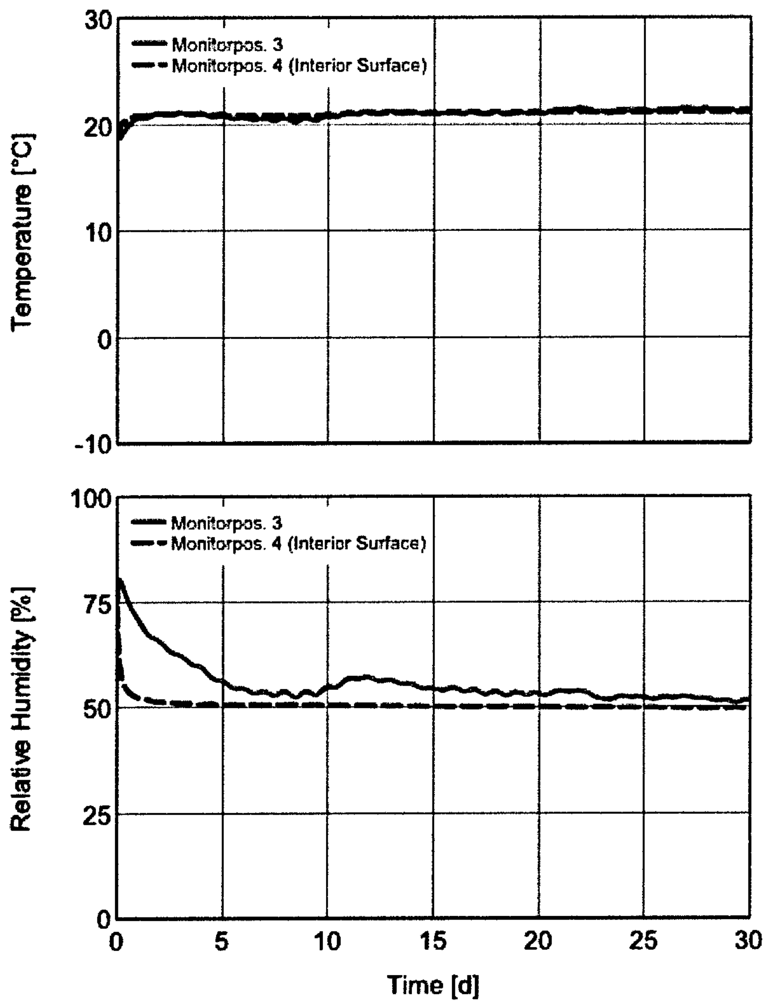
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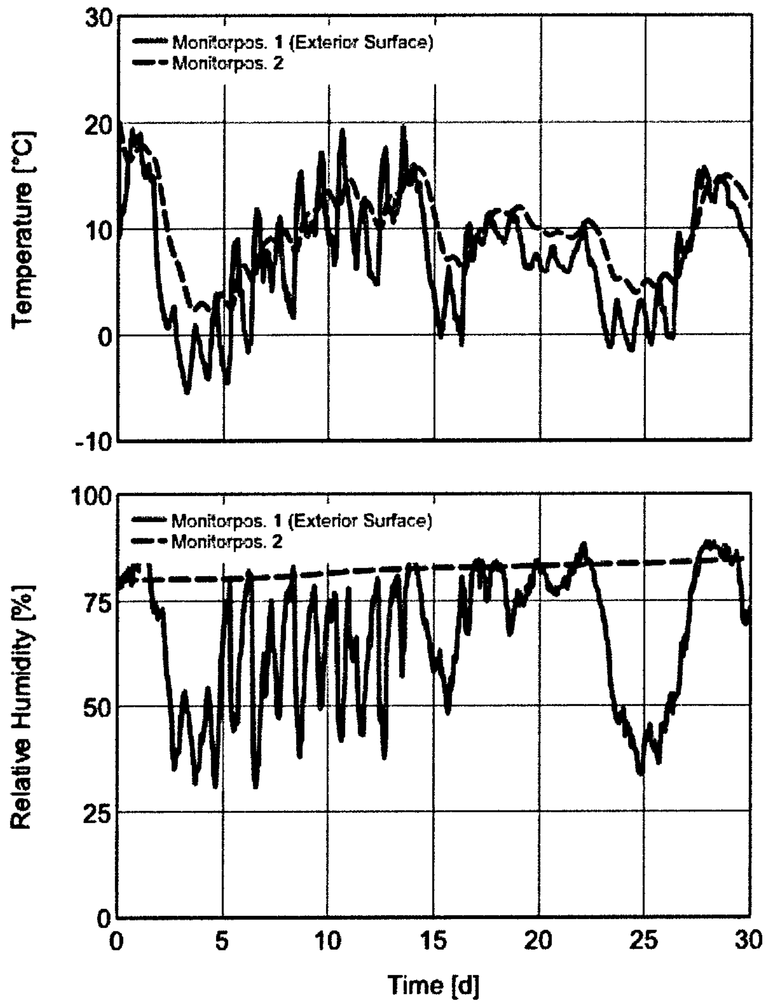
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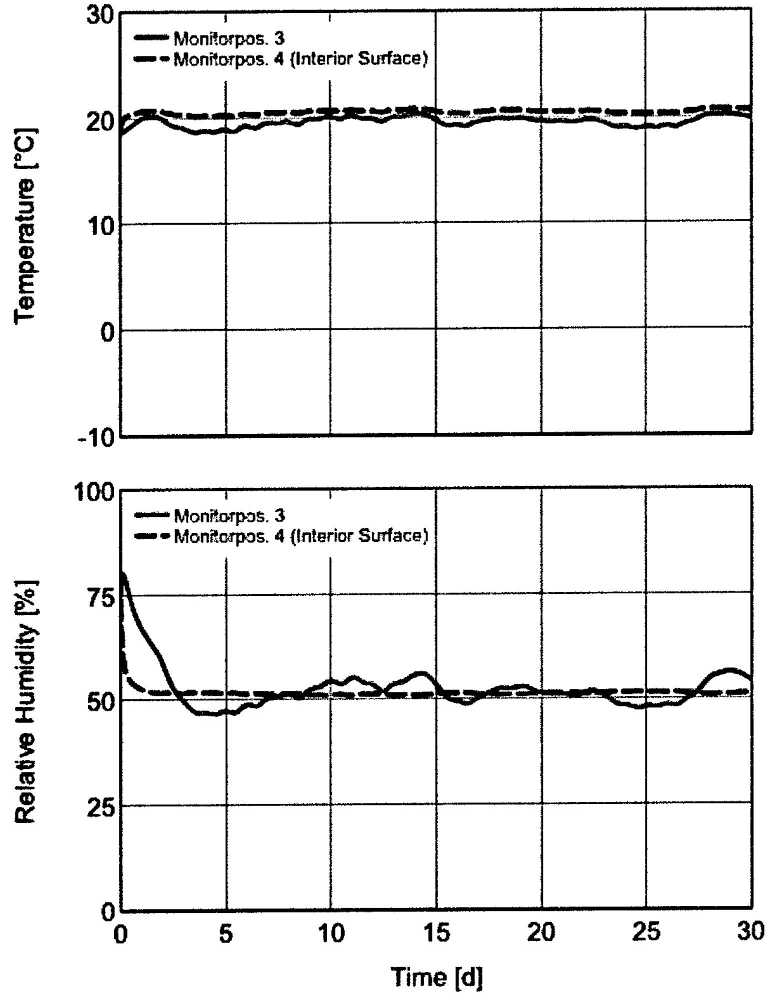
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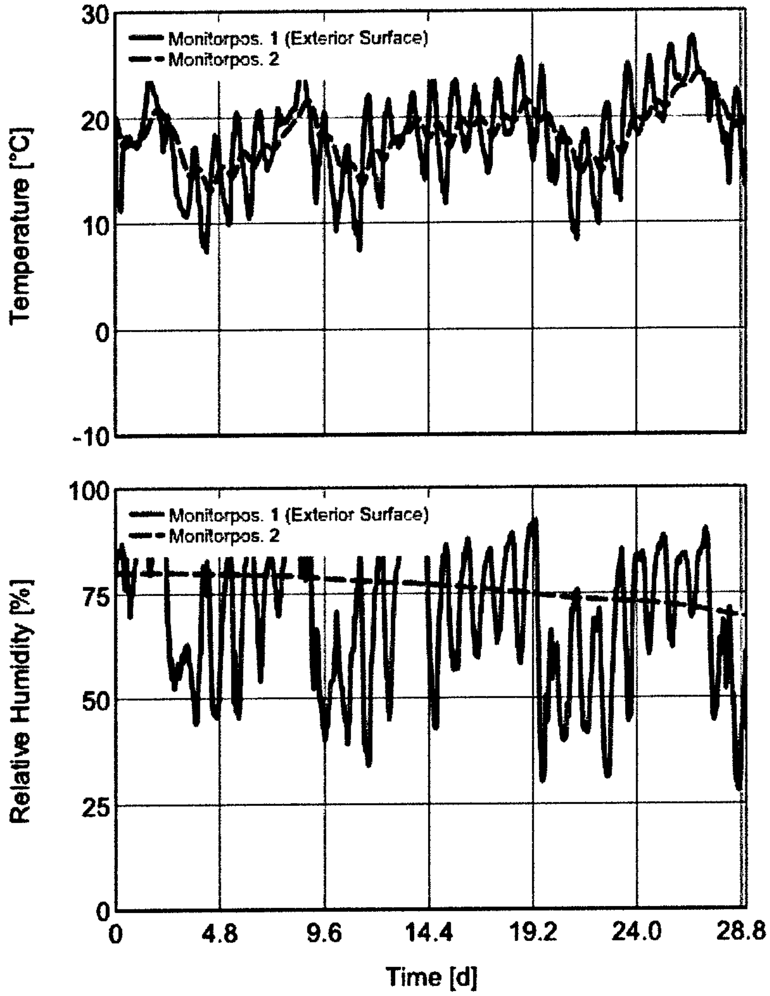
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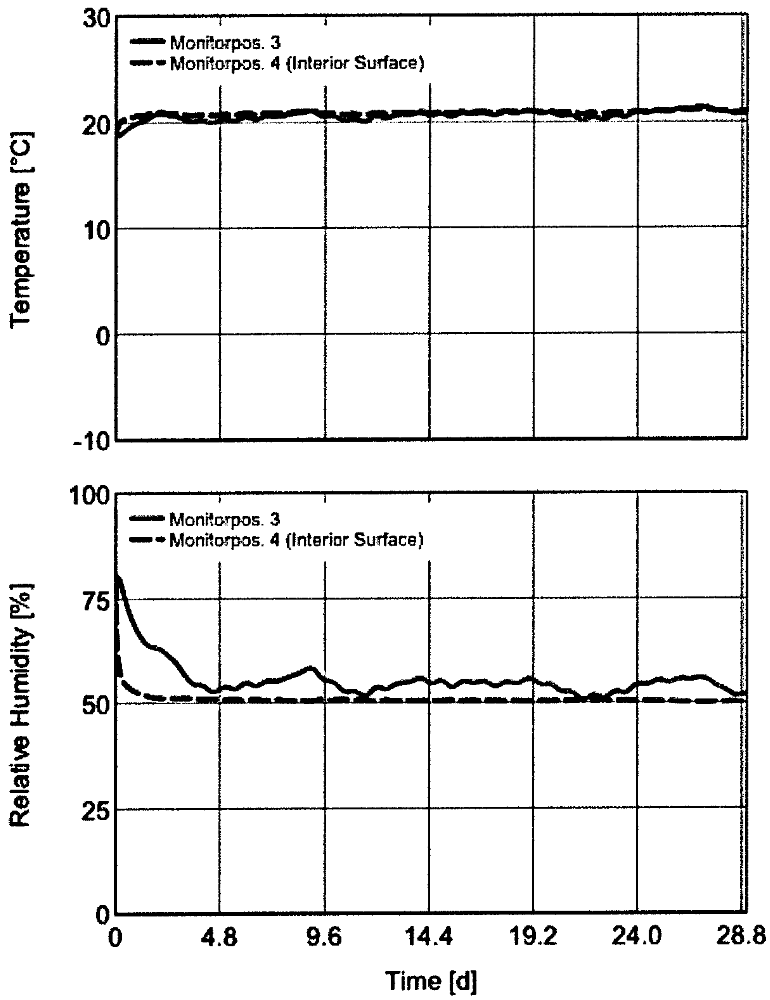
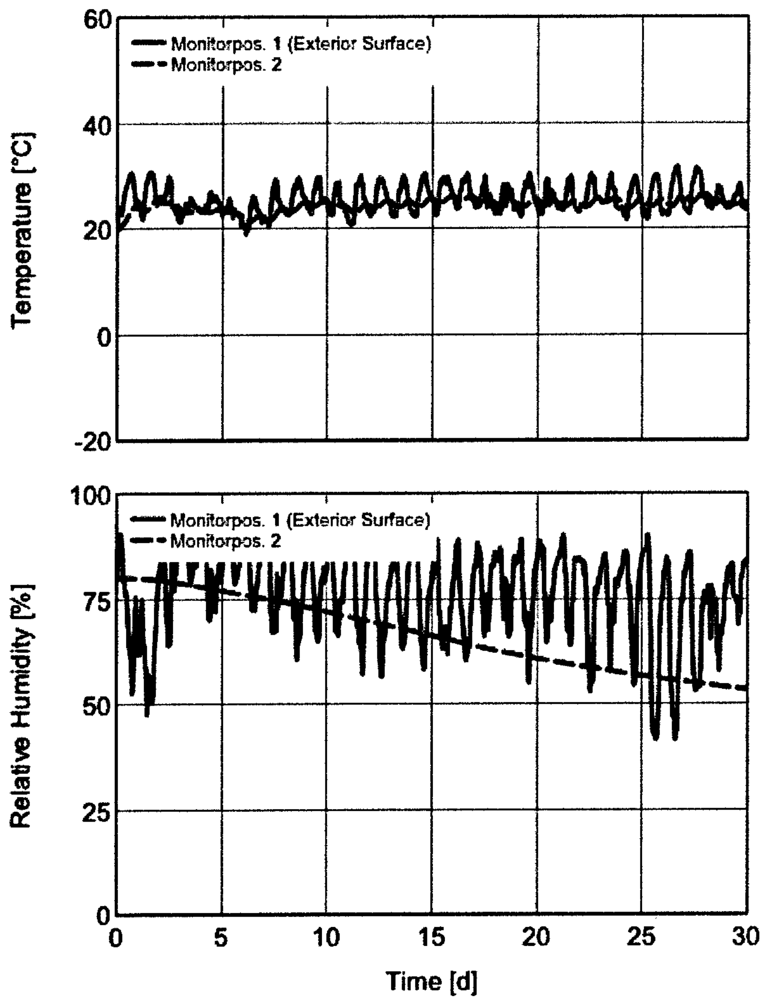
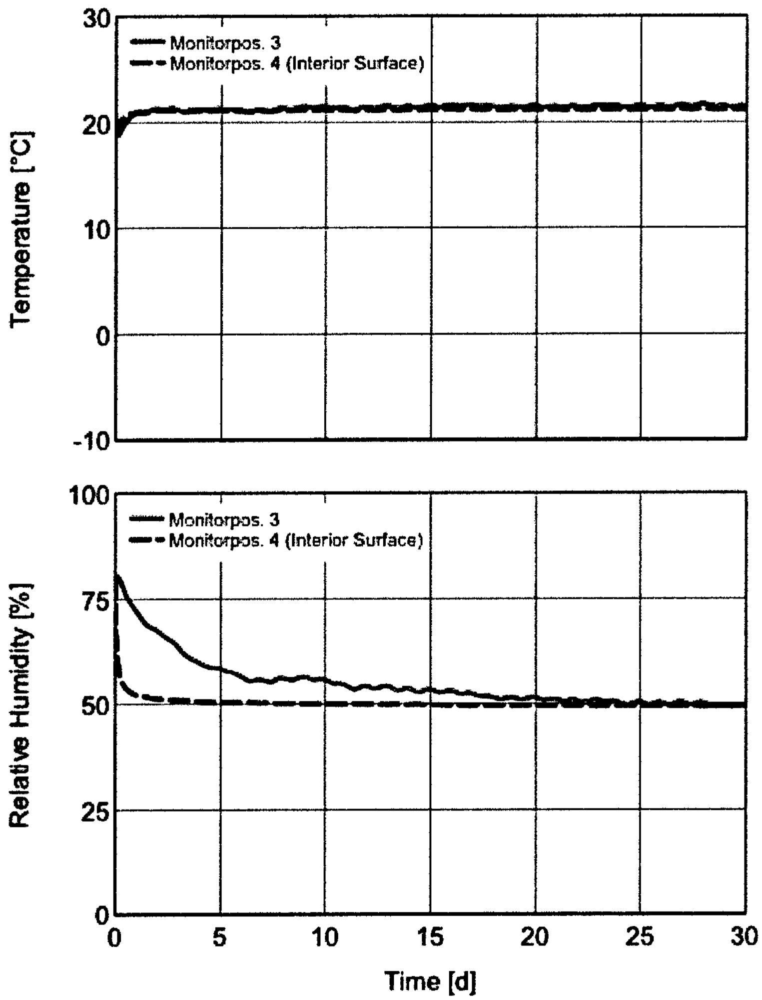
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



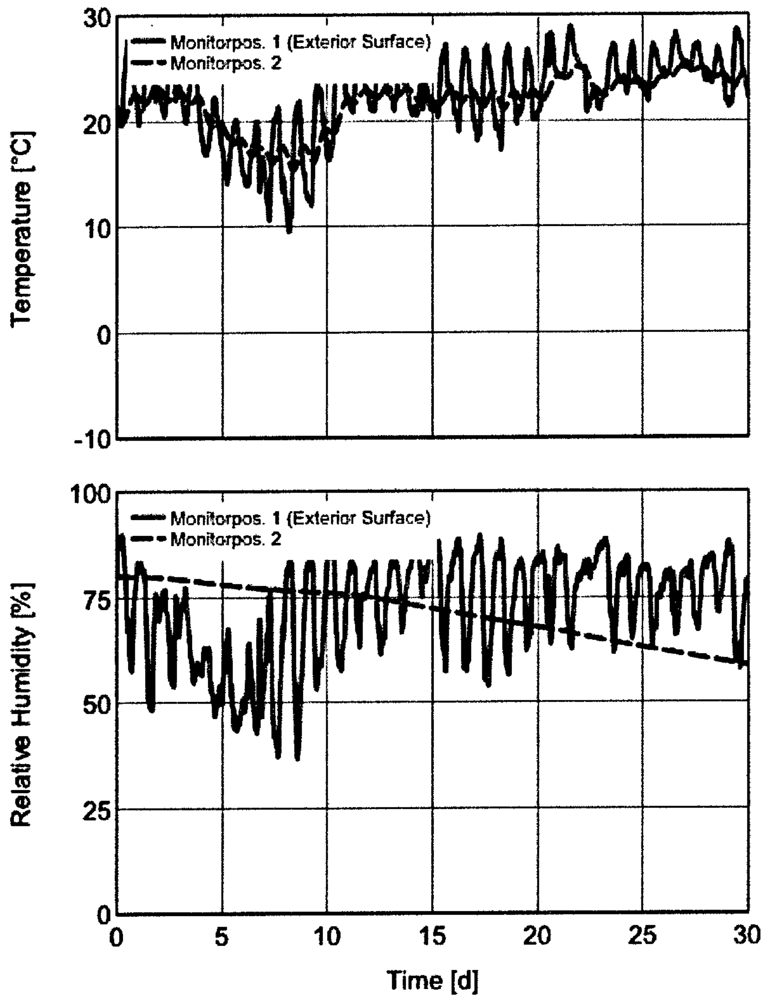
30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]

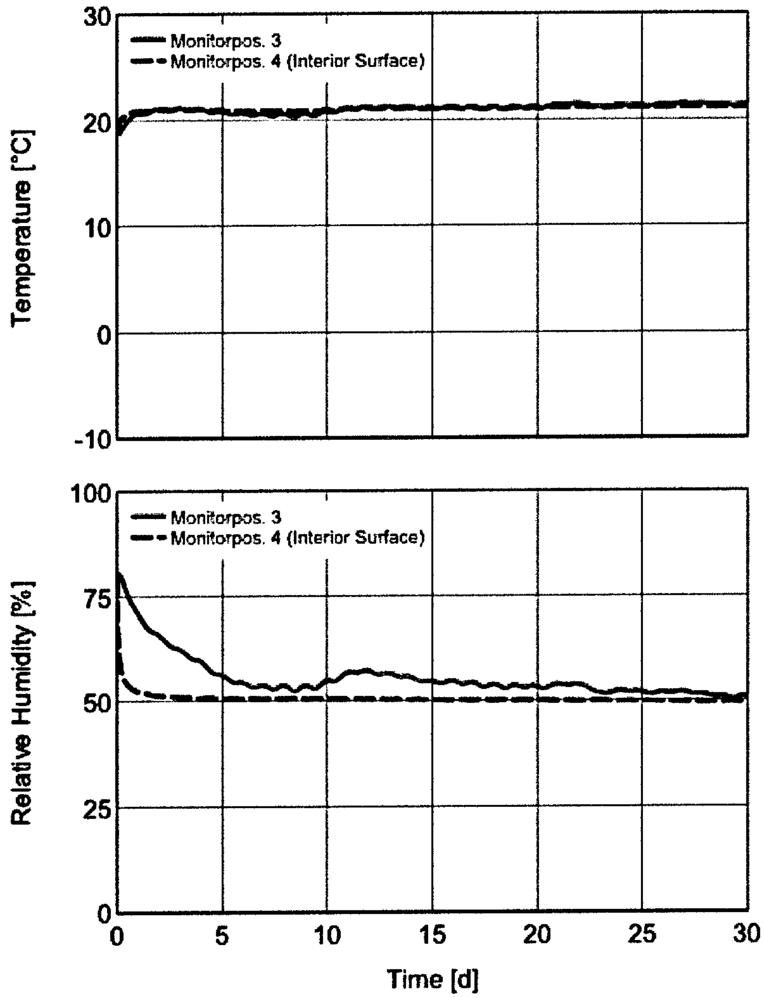


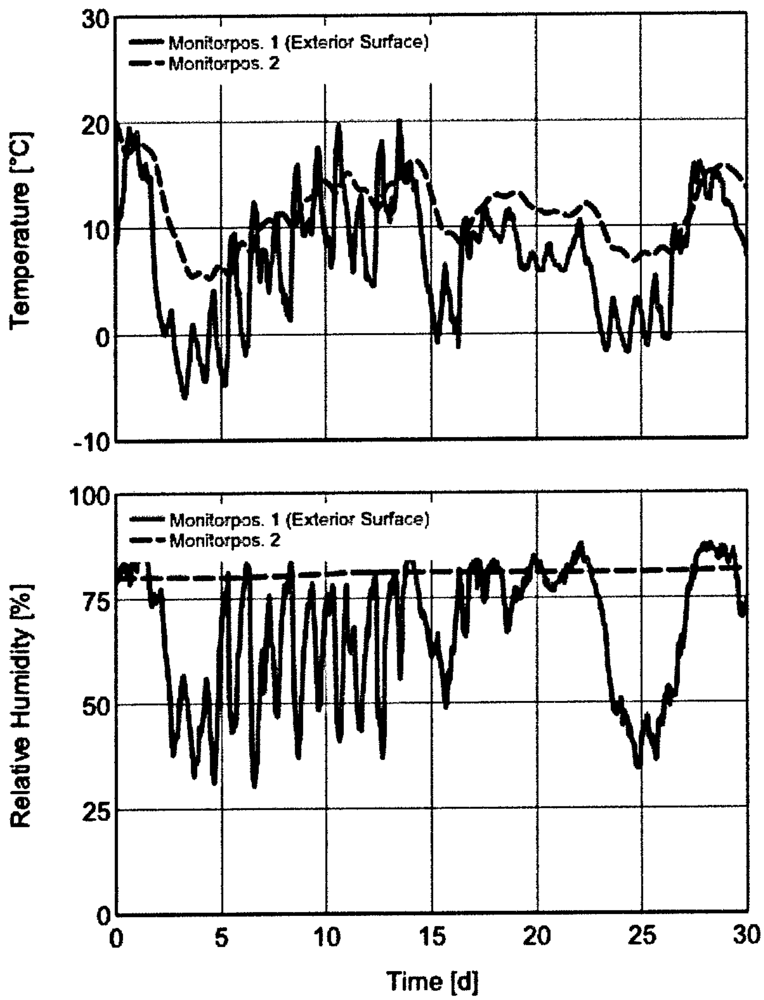
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
60
40
20
0
-20
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]



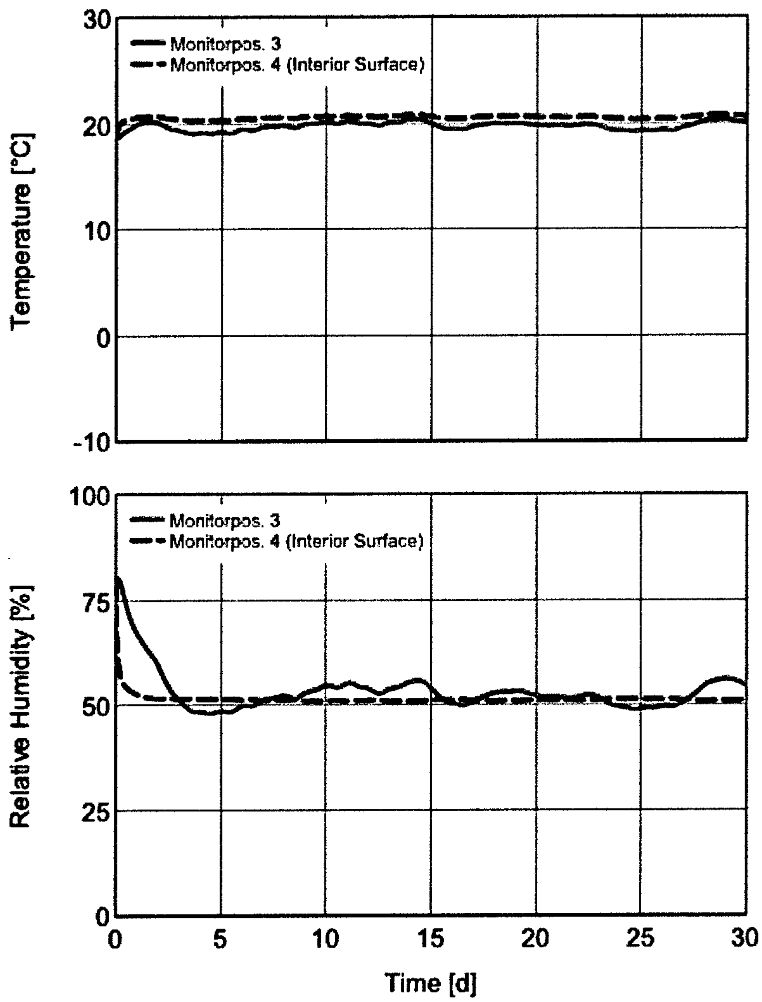
30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]


Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]


Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]



Project: Project and Report / Case 2: Spruce Siding Model - 2-NVB-NO-1-AC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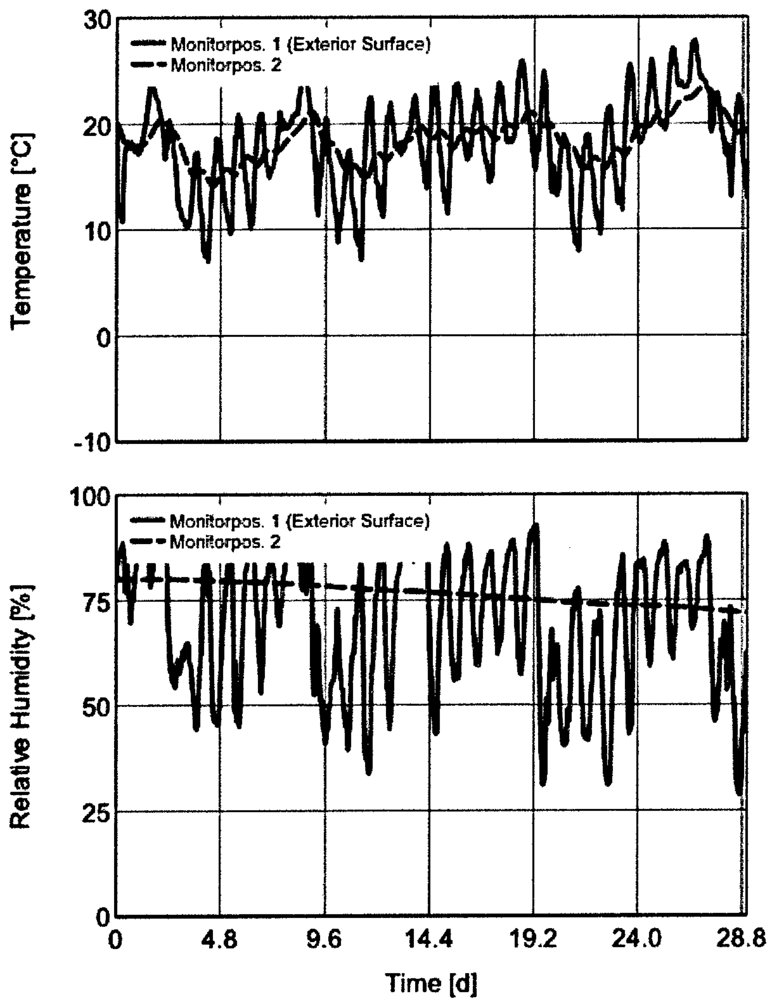
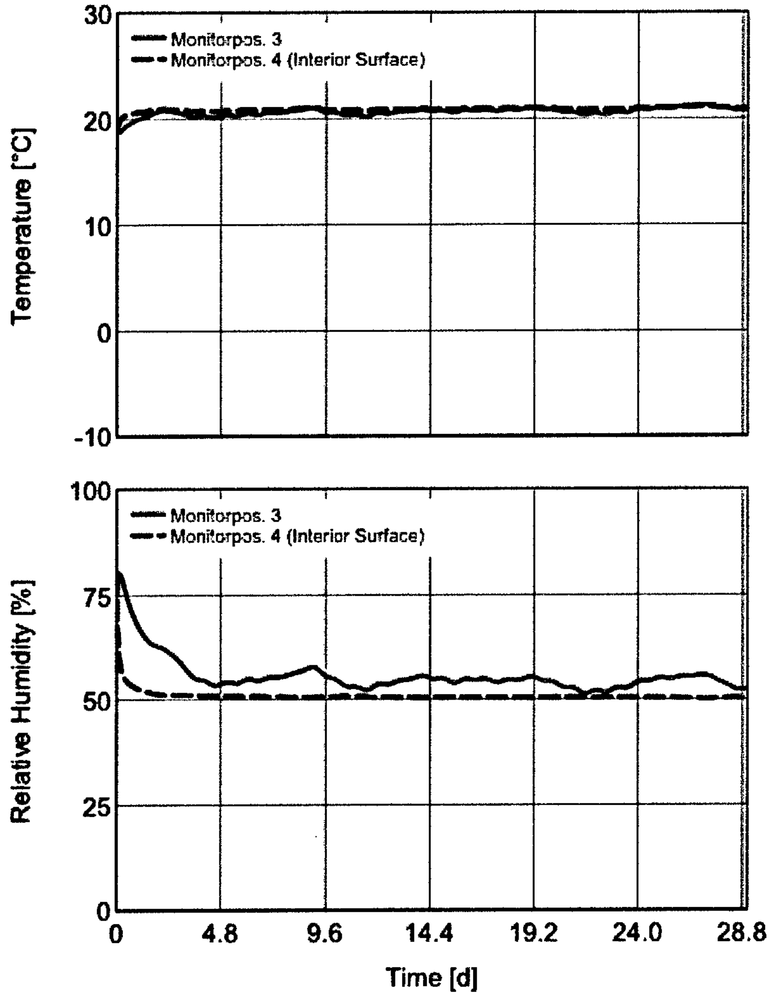
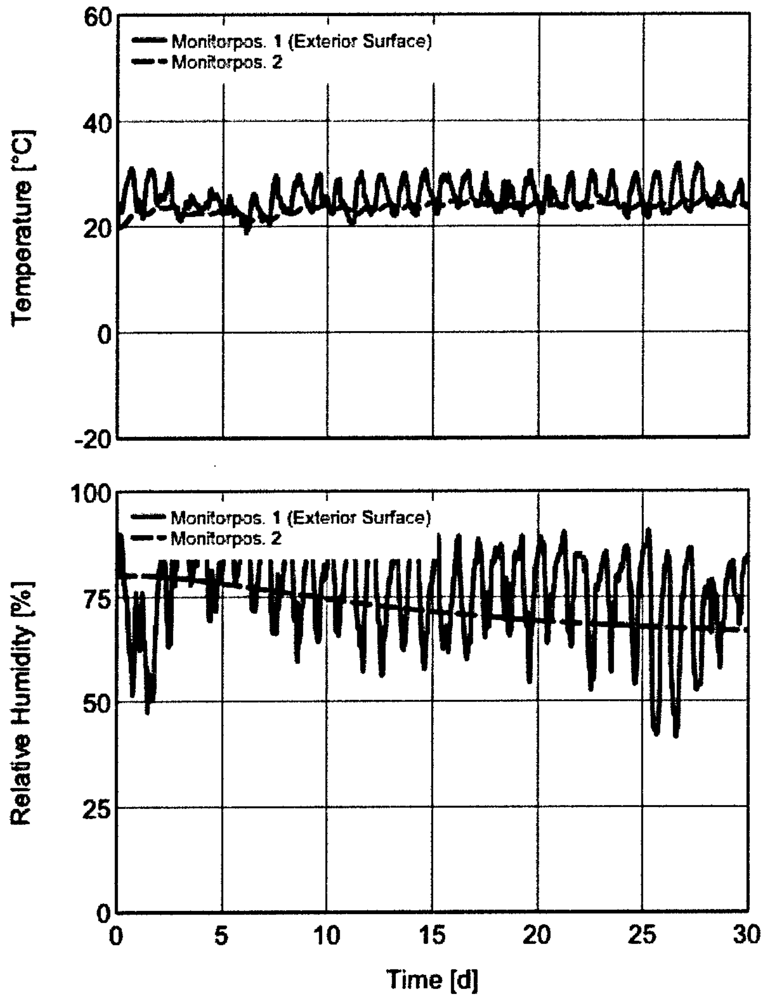
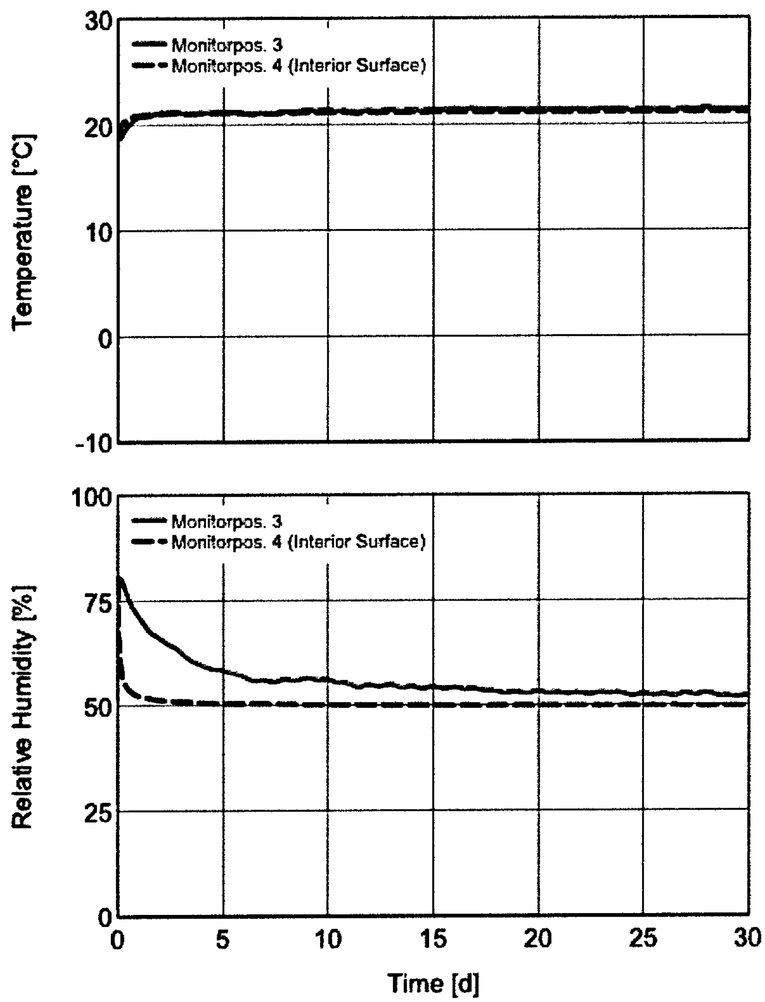
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]

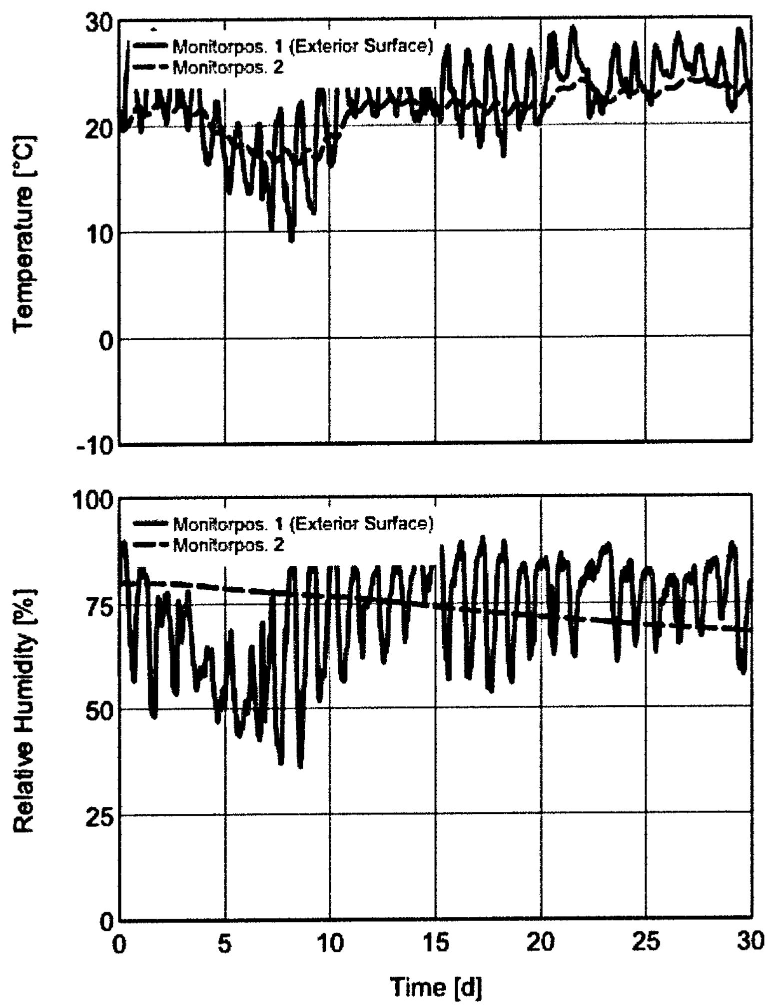

Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]


Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
60
40
20
0
-20
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]


30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]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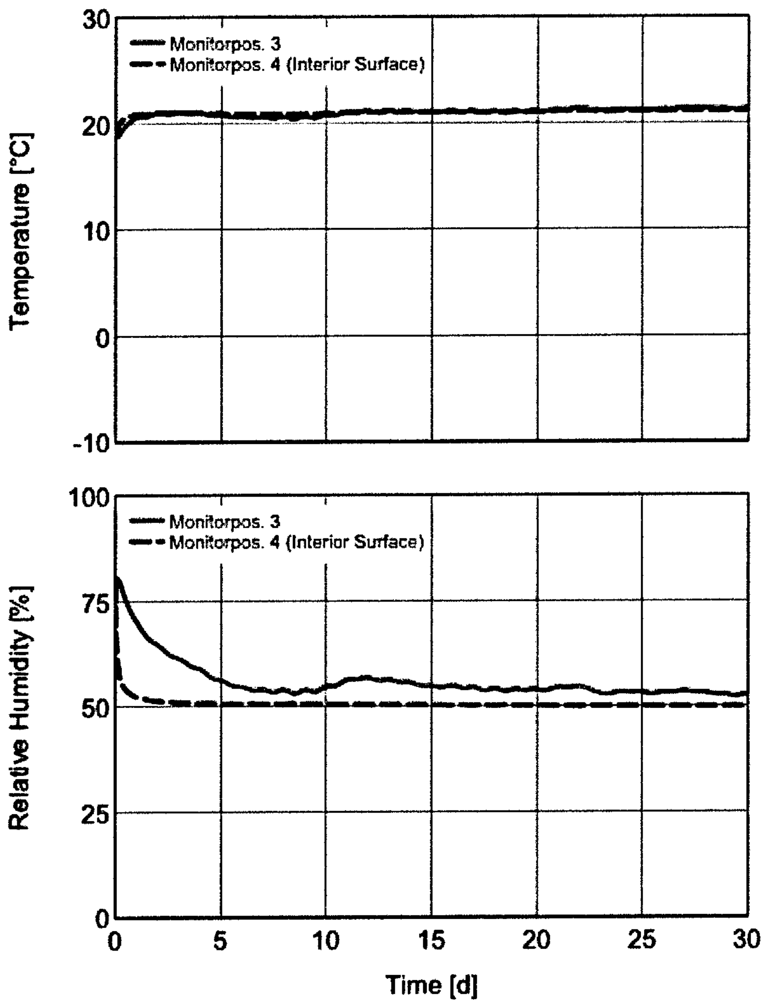
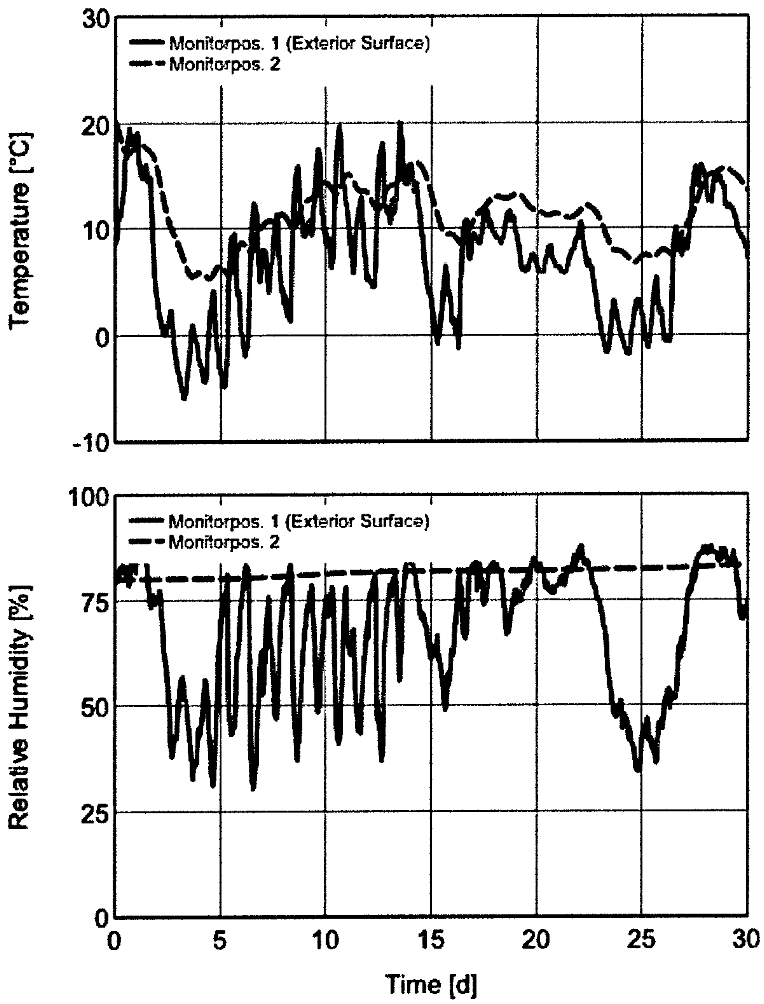
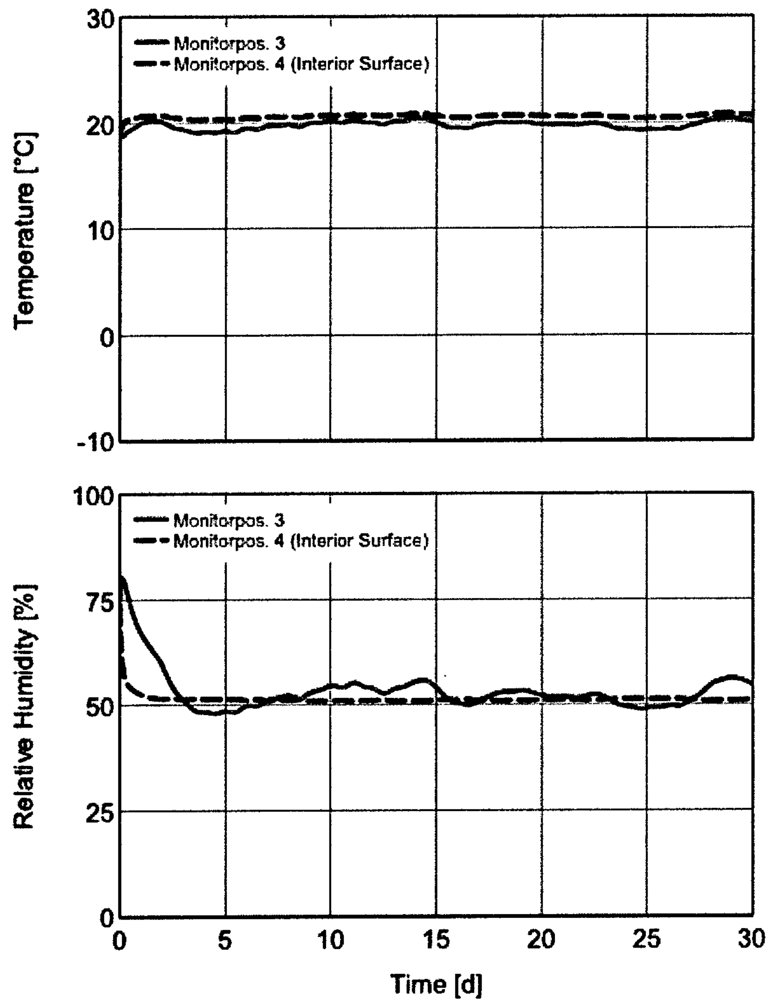
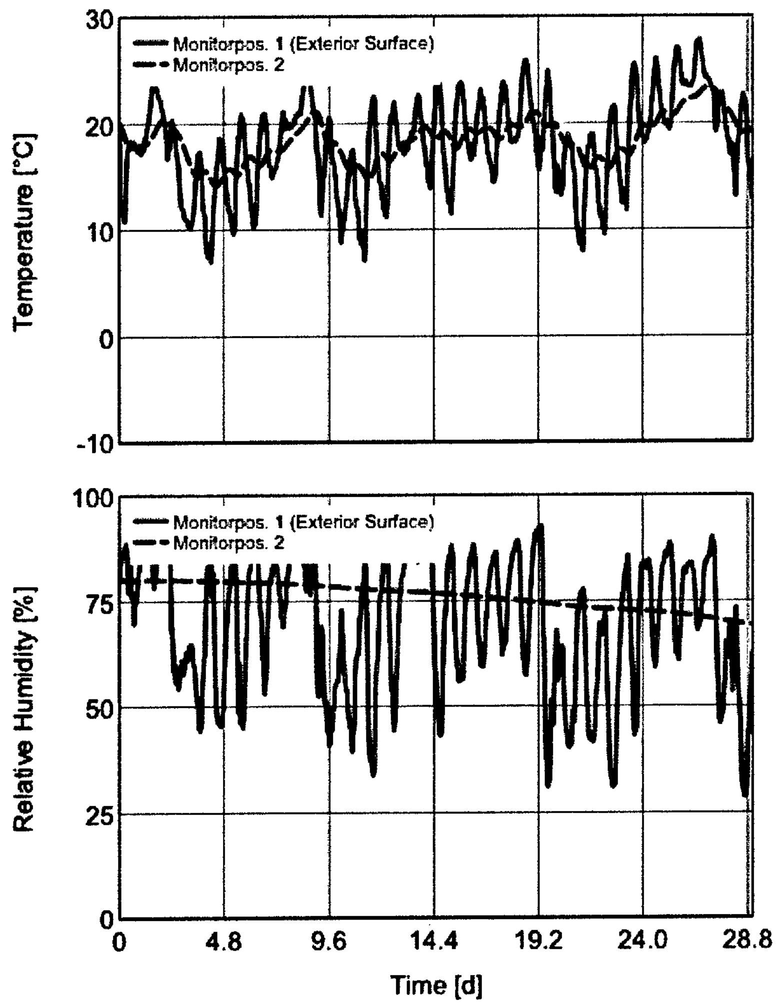
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]

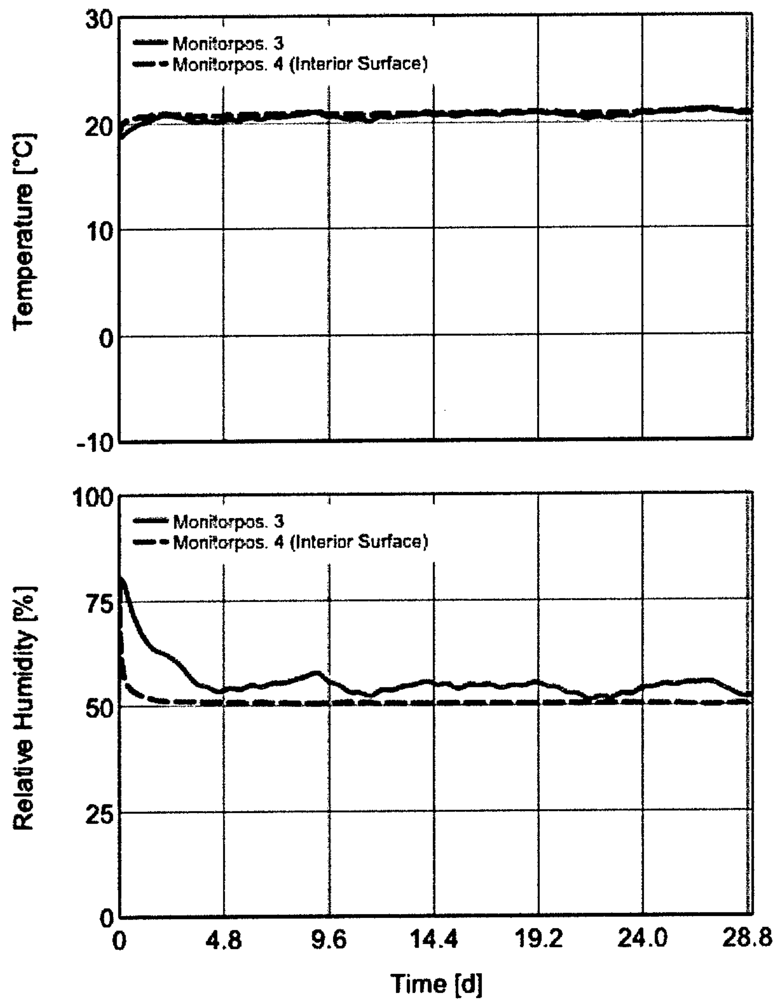


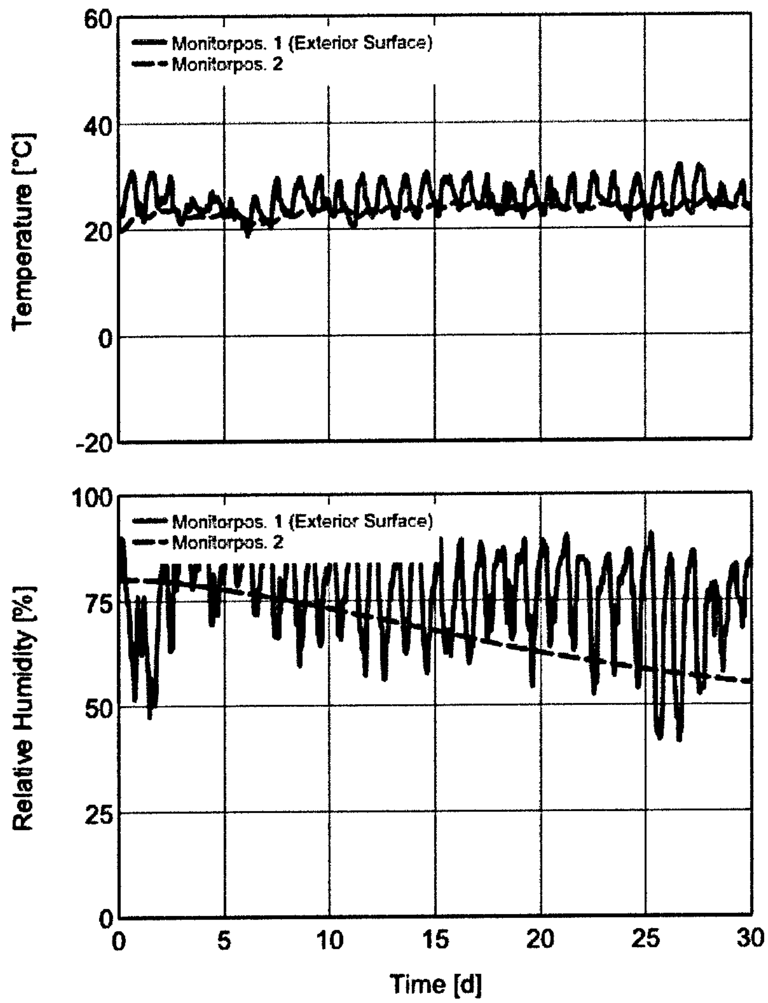
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]

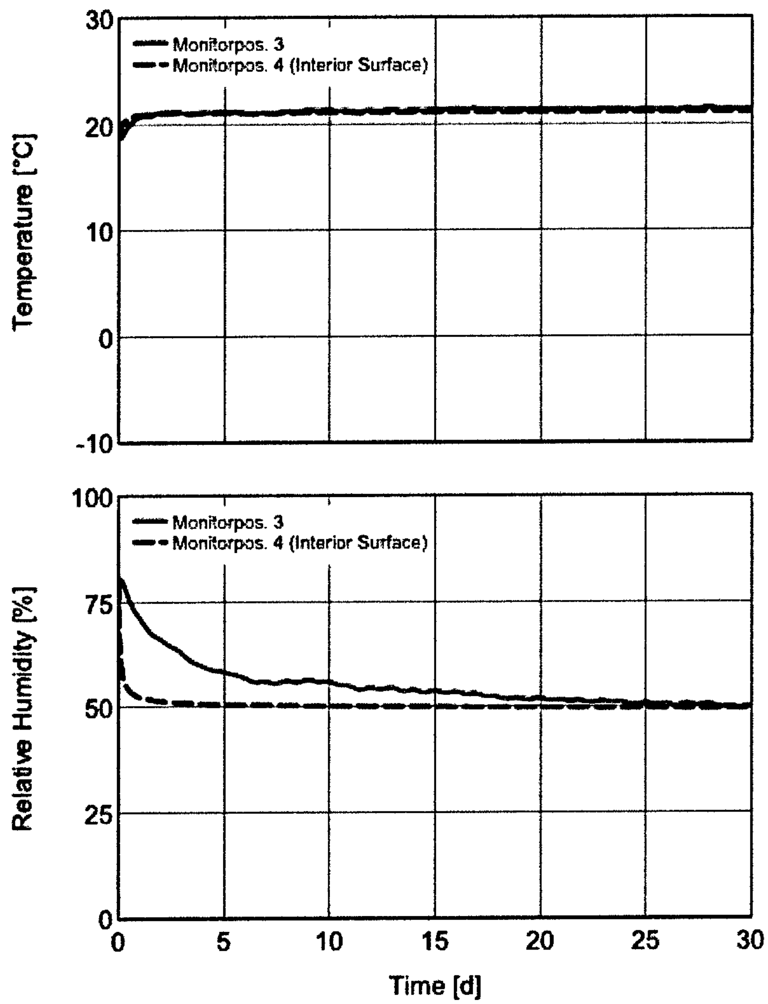

30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]

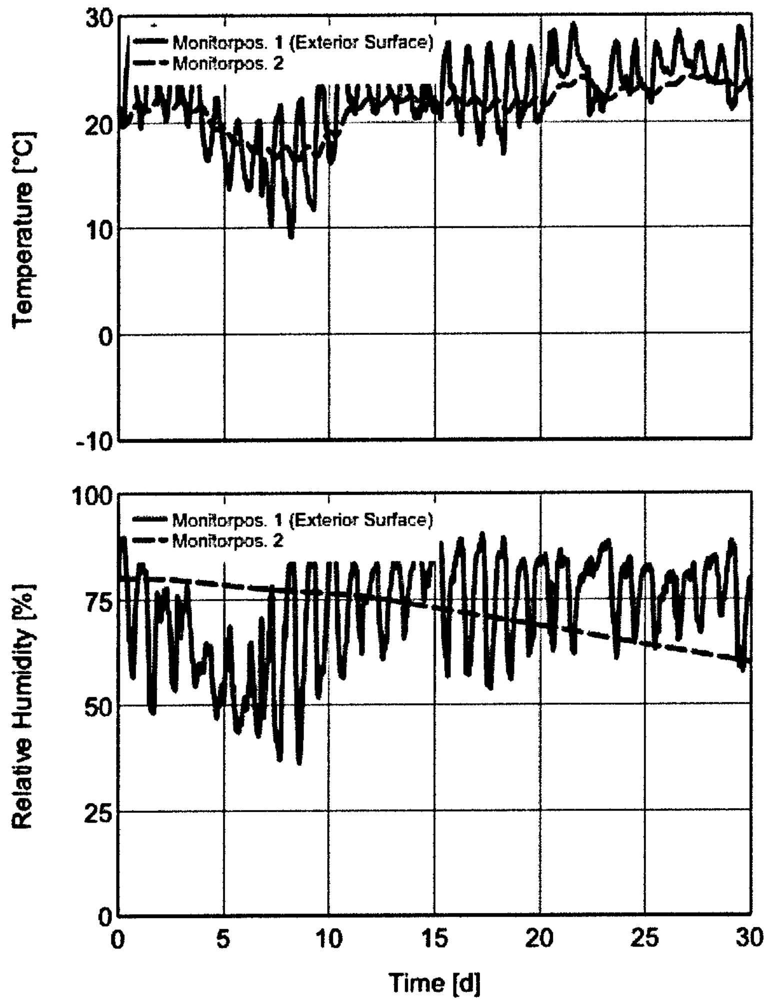

30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]


30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]

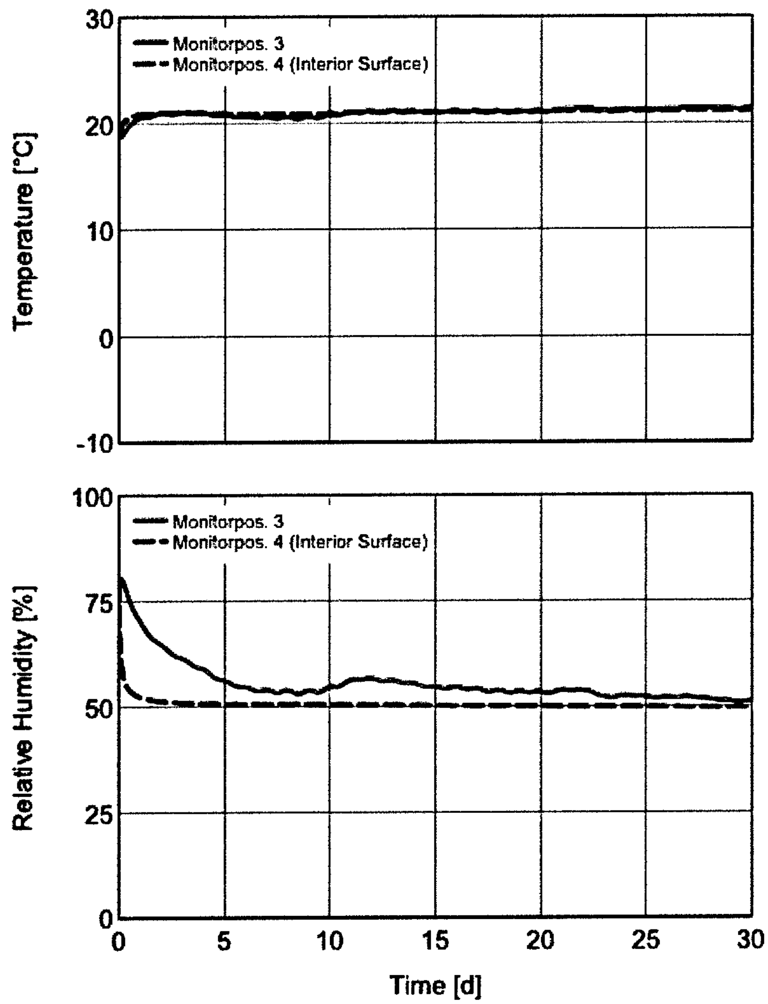

30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]


60
40
20
0
-20
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
100
75
50
25
0
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
0
5
10
15
20
25
30
Time [d]

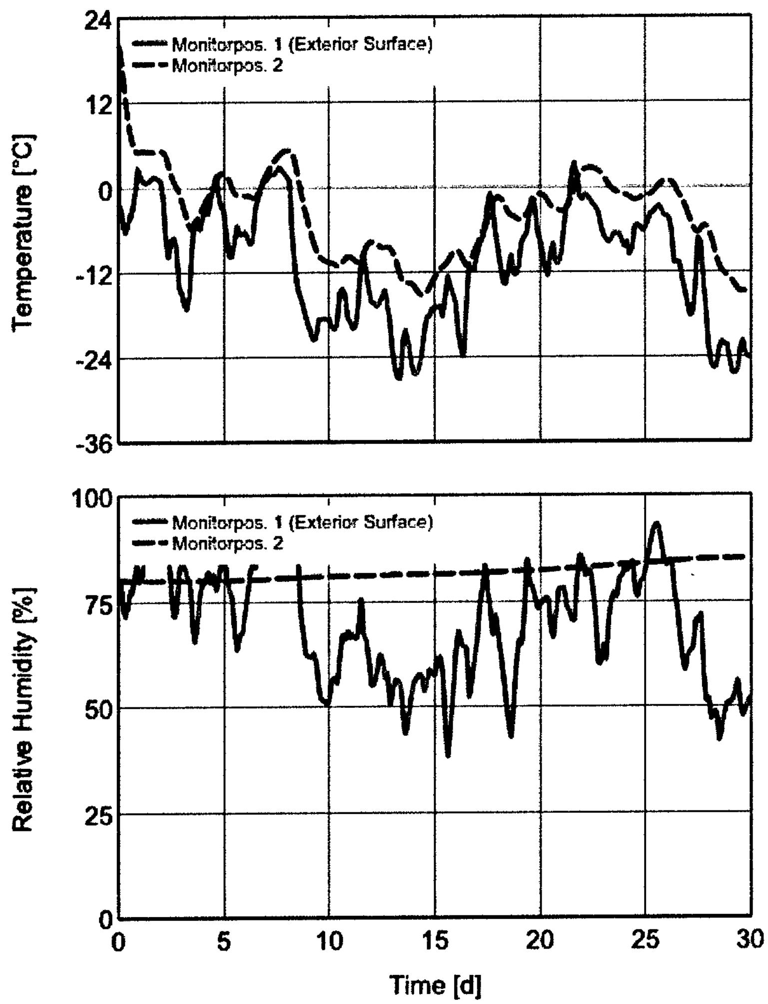

Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]



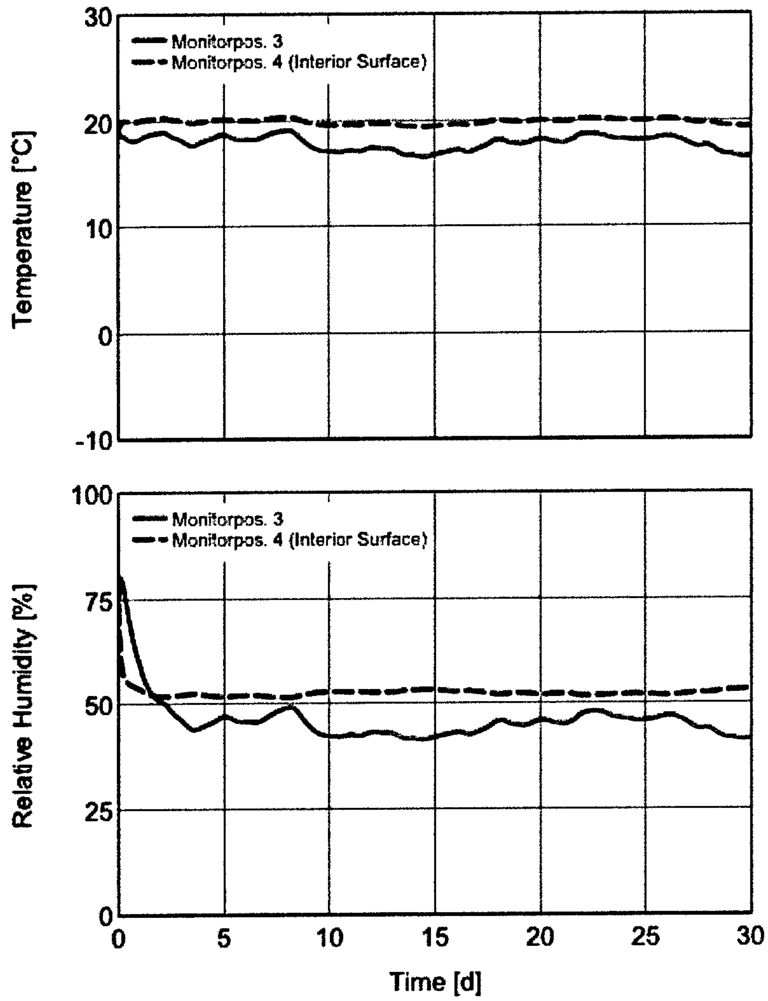
30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]

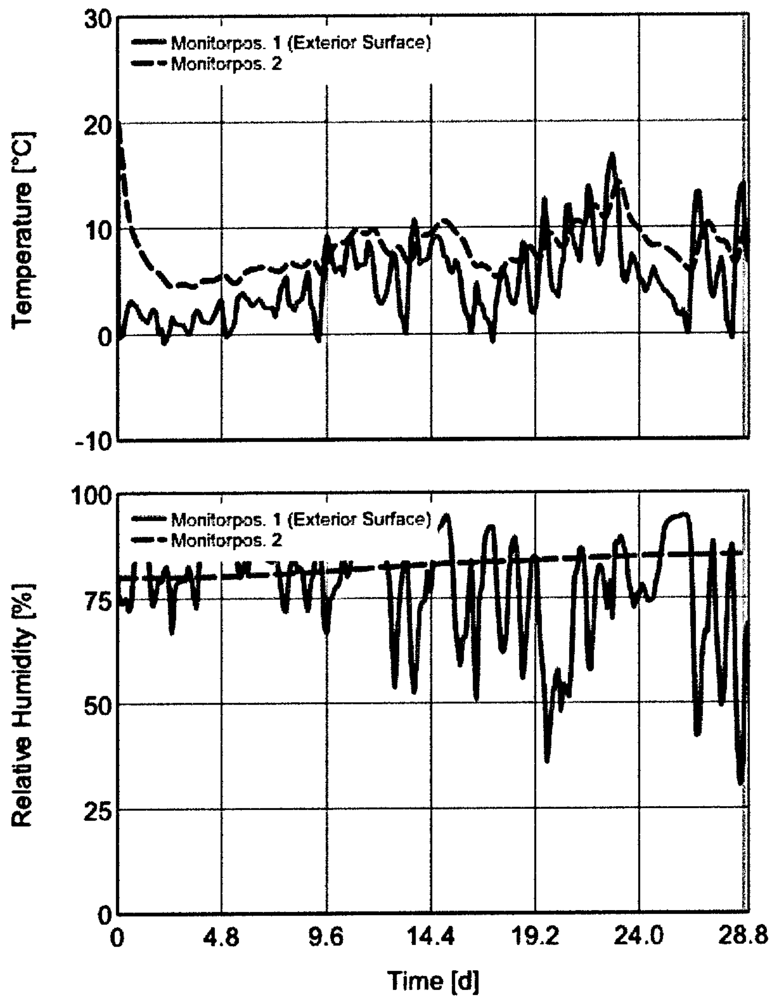

30
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
20
10
0
-10
Temperature [°C]
100
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
75
50
25
0
Relative Humidity [%]
0
5
10
15
20
25
30
Time [d]

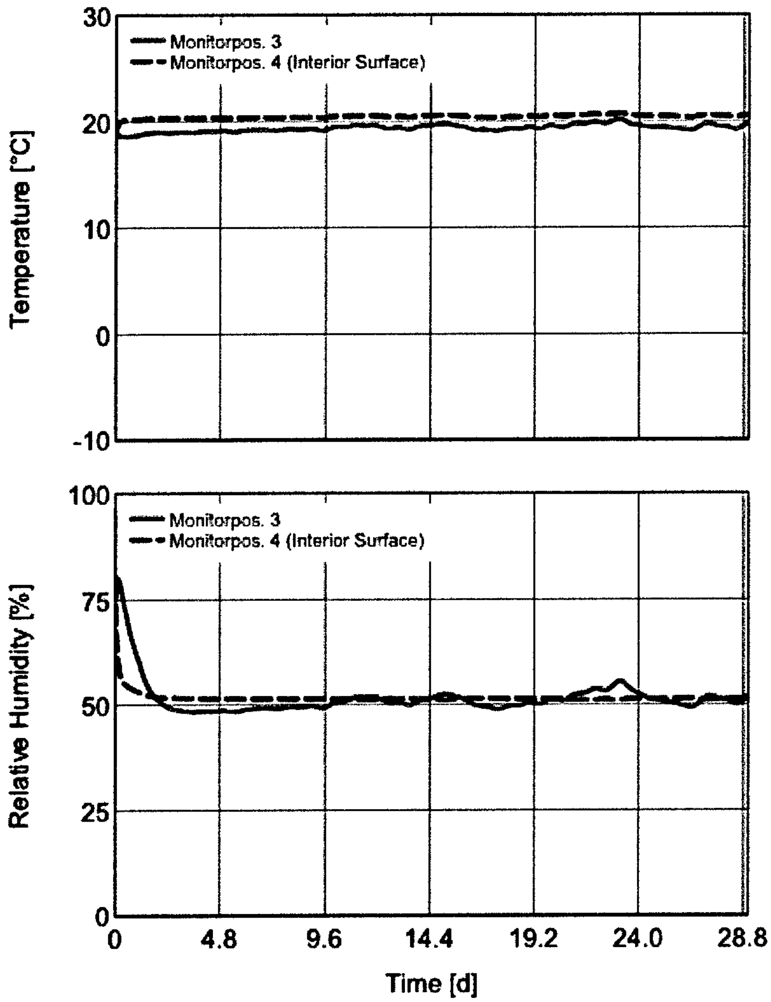
Appendix 2 – Minneapolis Test Data



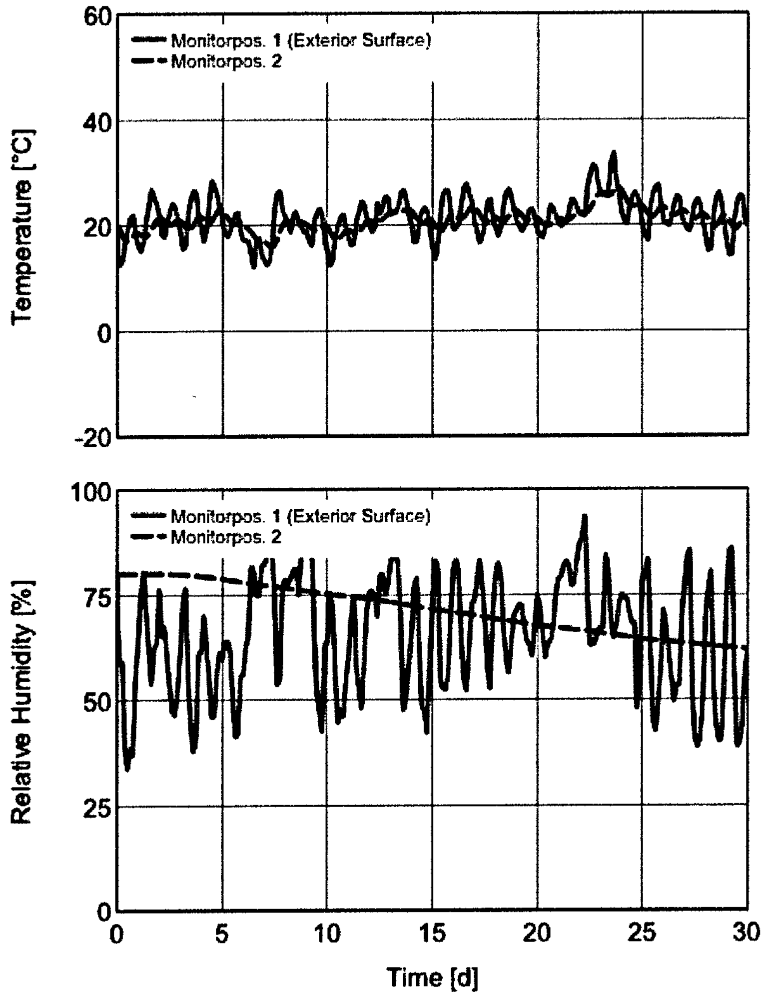
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
24
12
0
-12
-24
-36
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]


30
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
20
10
0
-10
Temperature [°C]
100
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
75
50
25
0
Relative Humidity [%]
0
5
10
15
20
25
30
Time [d]

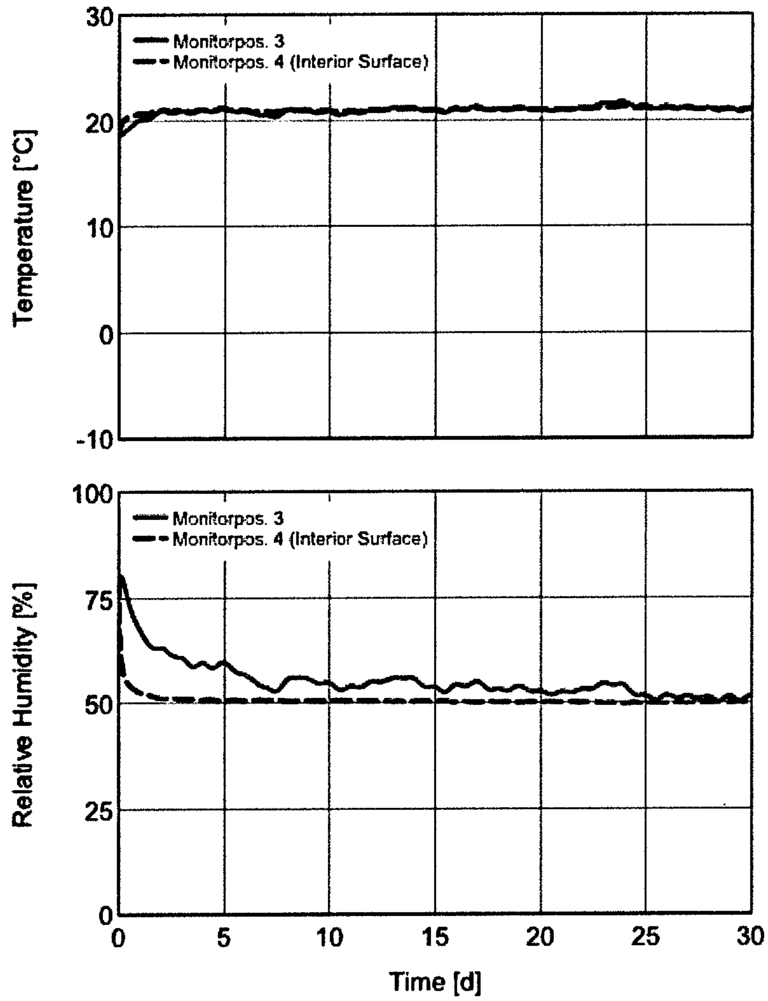

30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



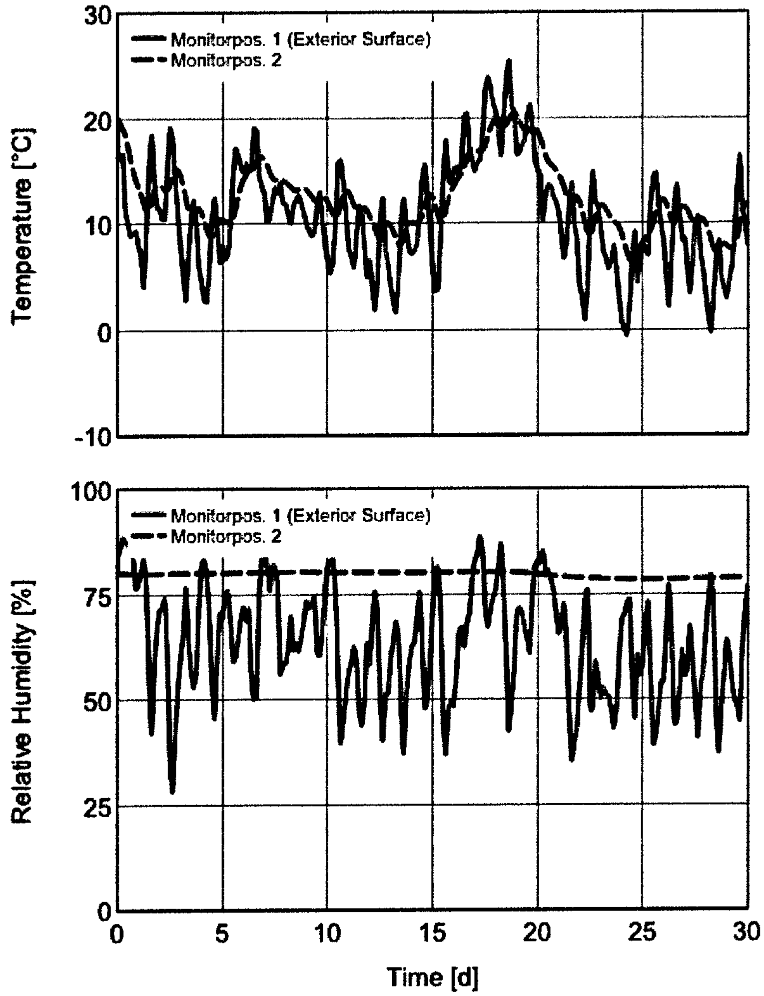
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]

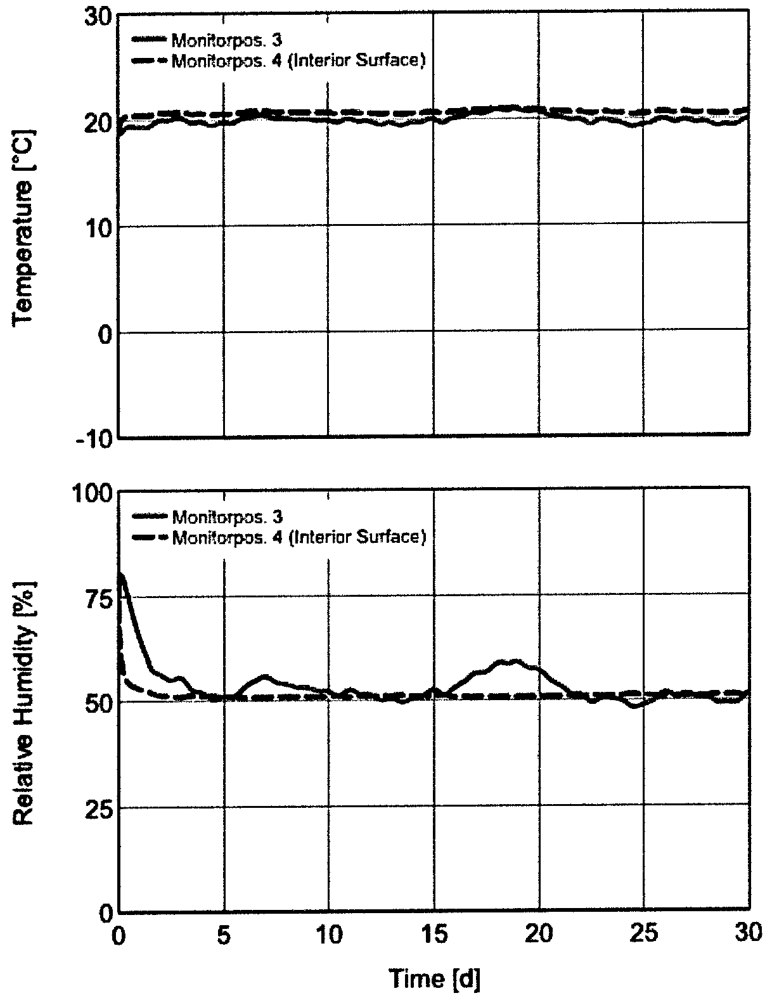


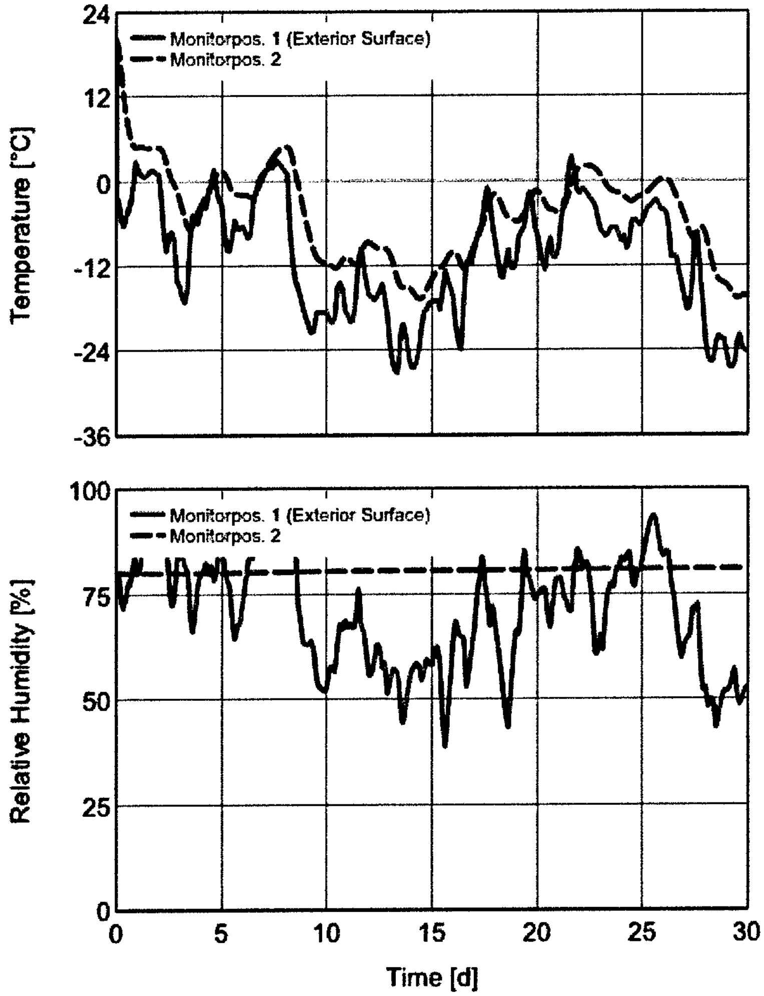
60
40
20
0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]



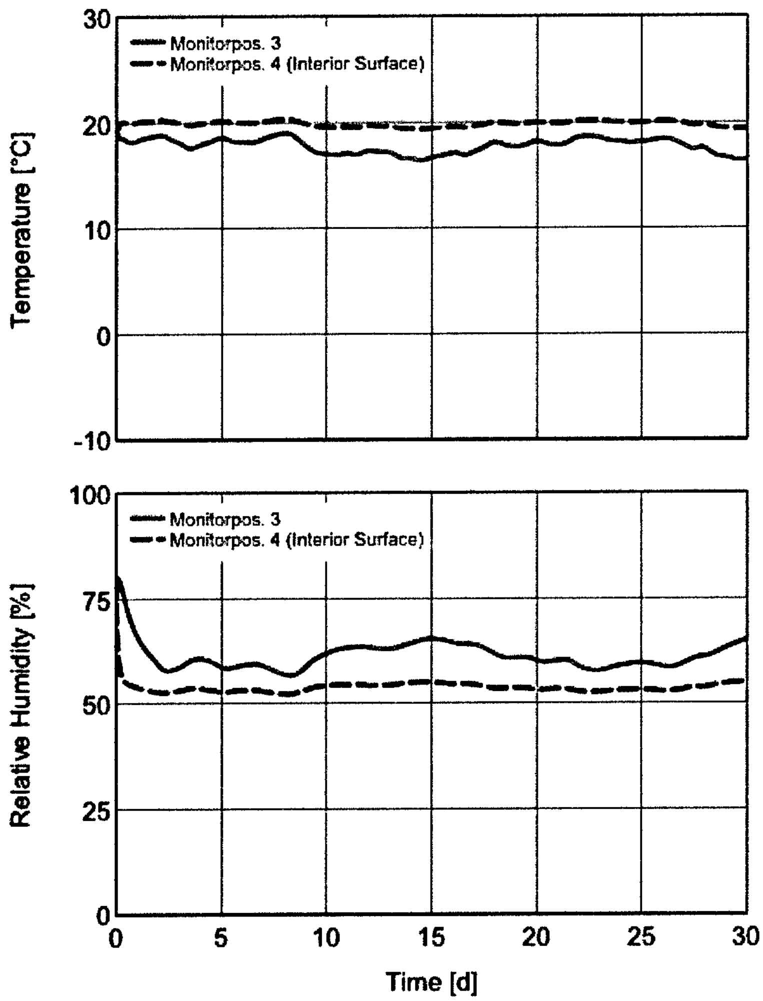
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]

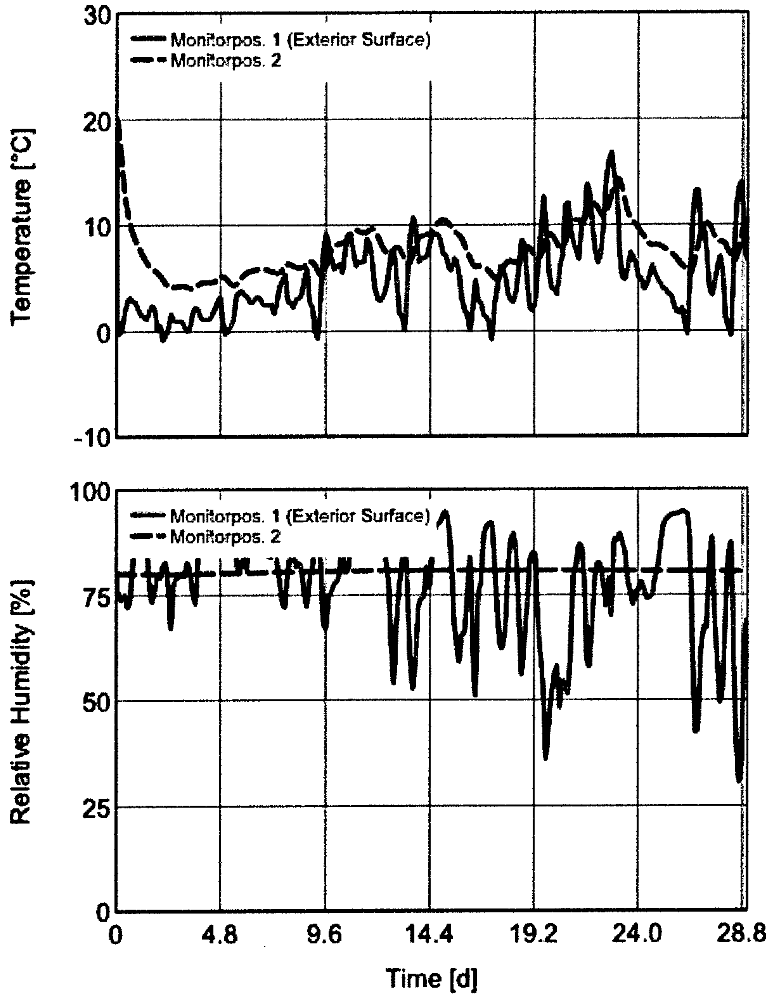

30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]


30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]

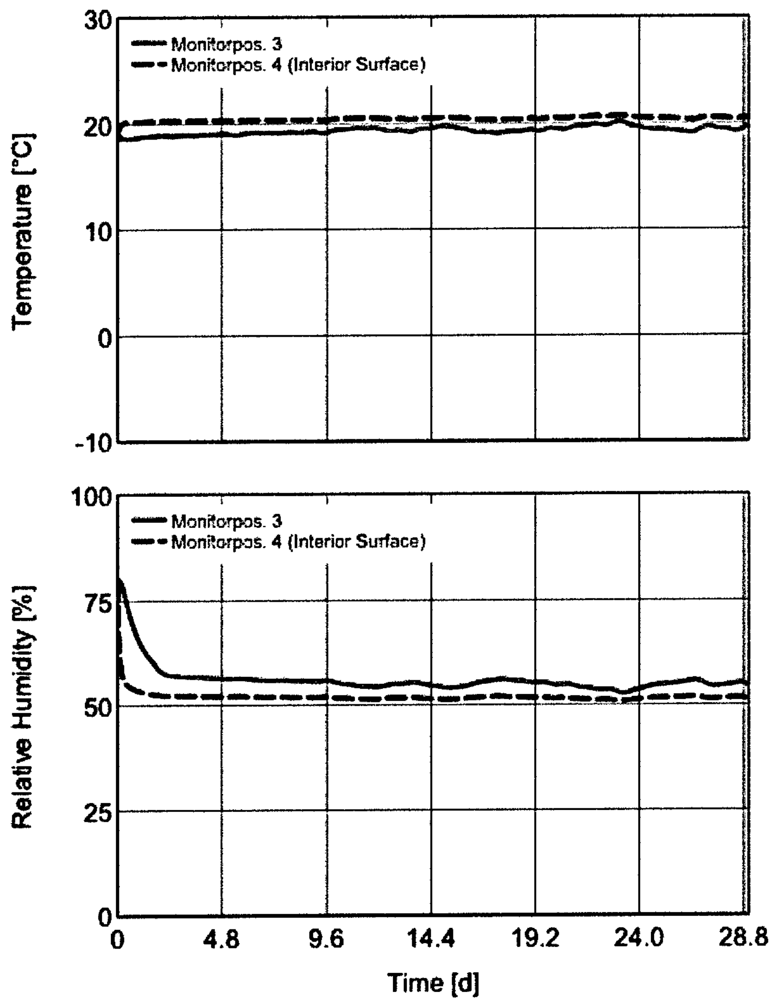


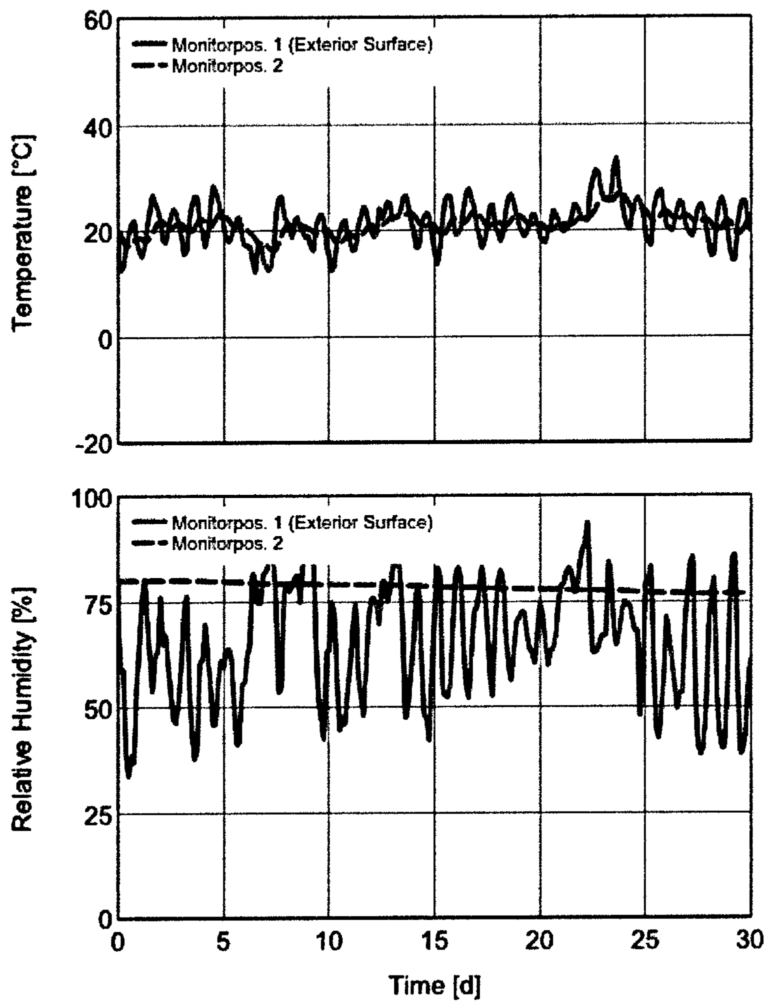
24
12
0
-12
-24
-36
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]

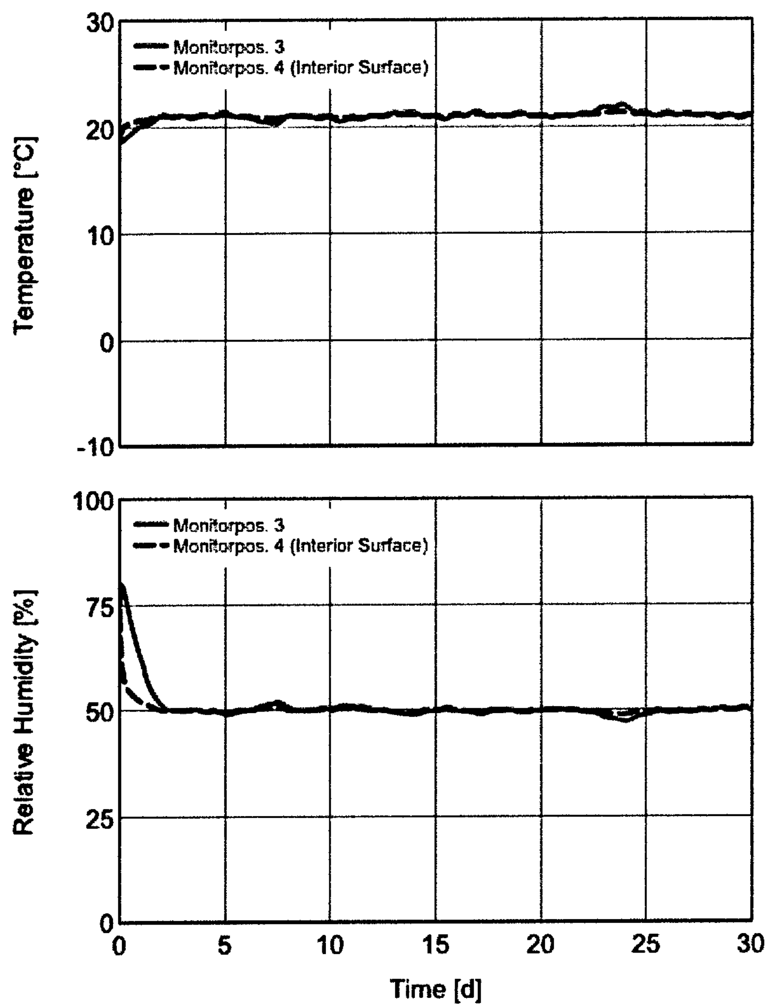

30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]

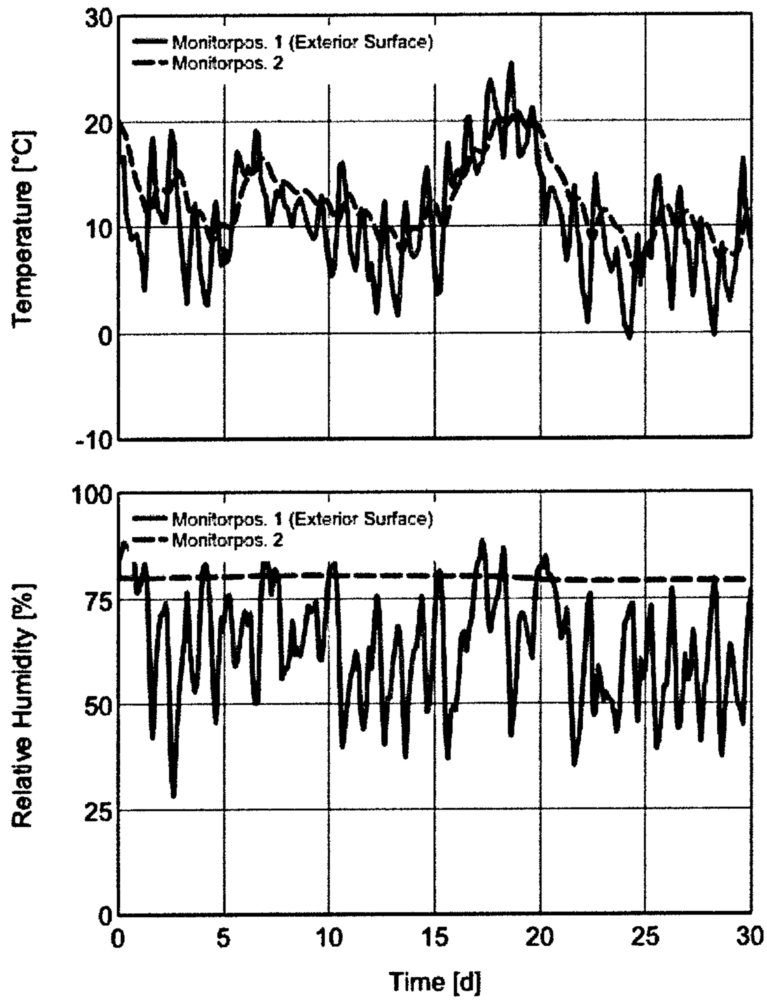


30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]

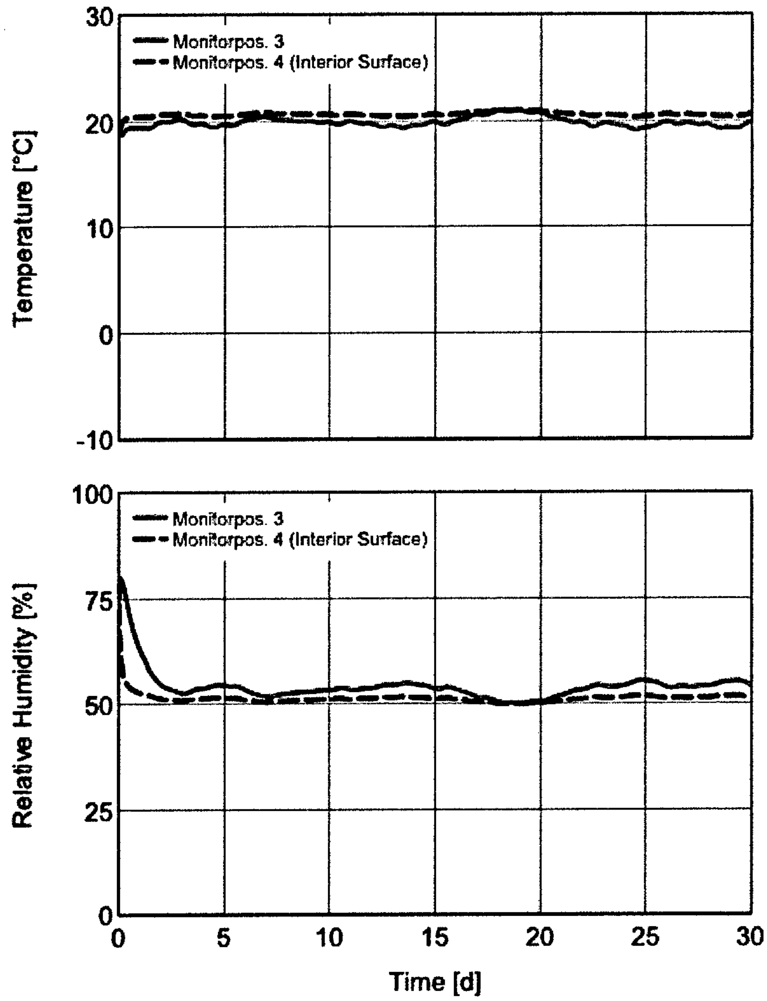

Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]


60
40
20
0
-20
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
100
75
50
25
0
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
0
5
10
15
20
25
30
Time [d]

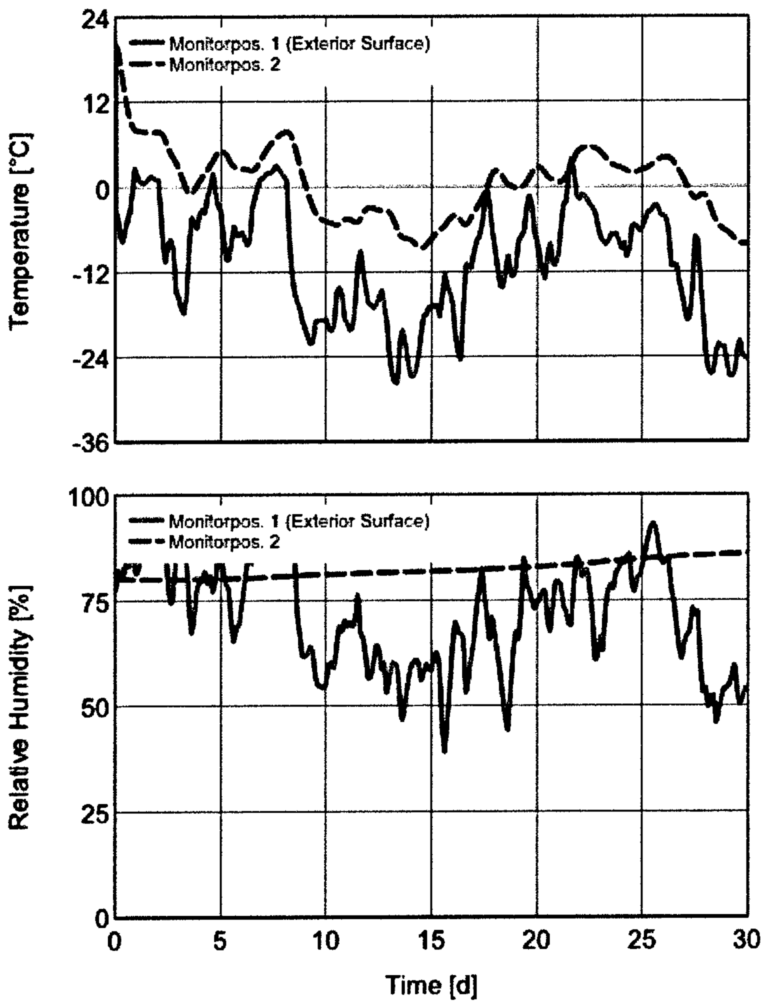

30
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
20
10
0
-10
Temperature [°C]
100
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
75
50
25
0
Relative Humidity [%]
0
5
10
15
20
25
30
Time [d]

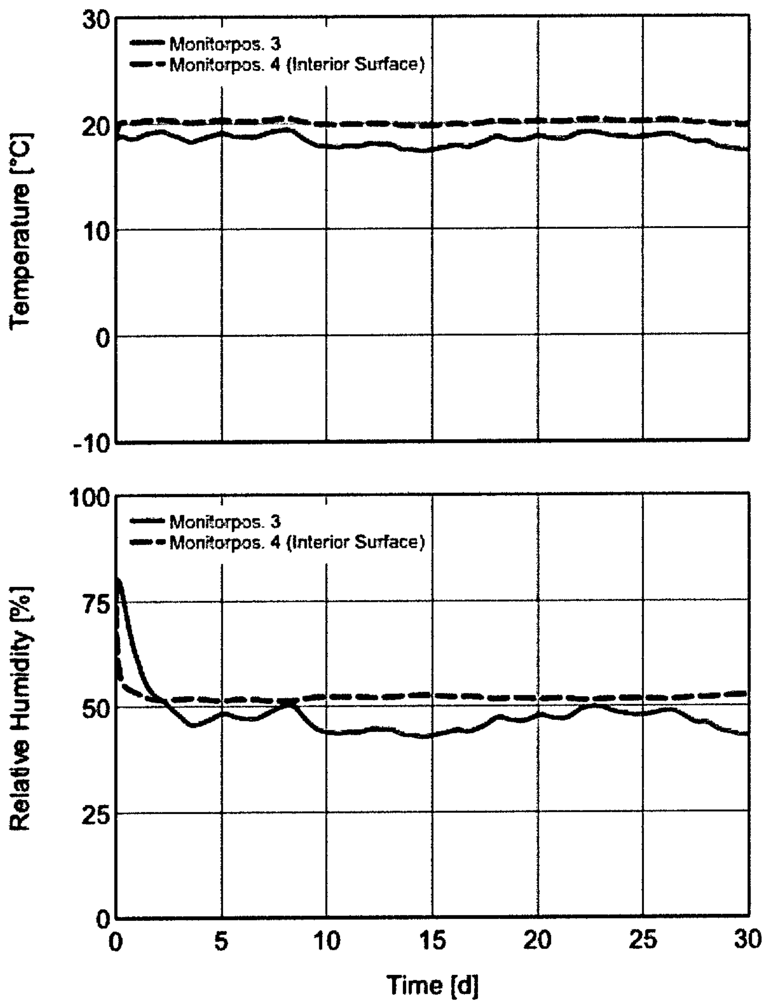


30
20
10
0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]



Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]


24
12
0
-12
-24
-36
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]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20
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0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
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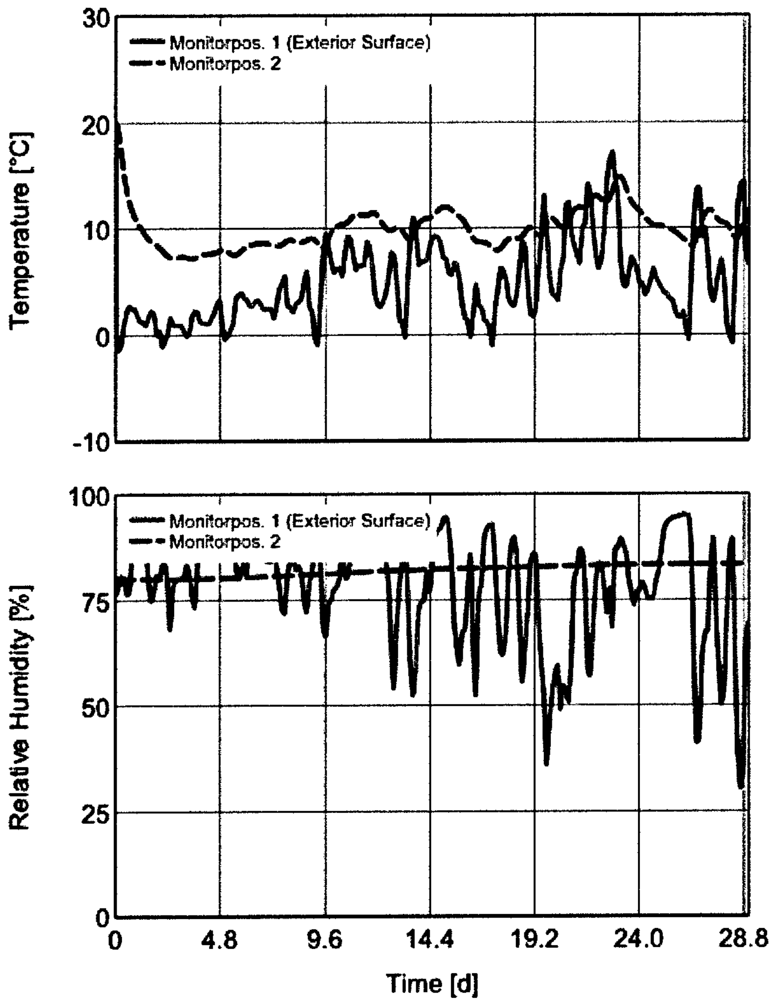
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]



Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
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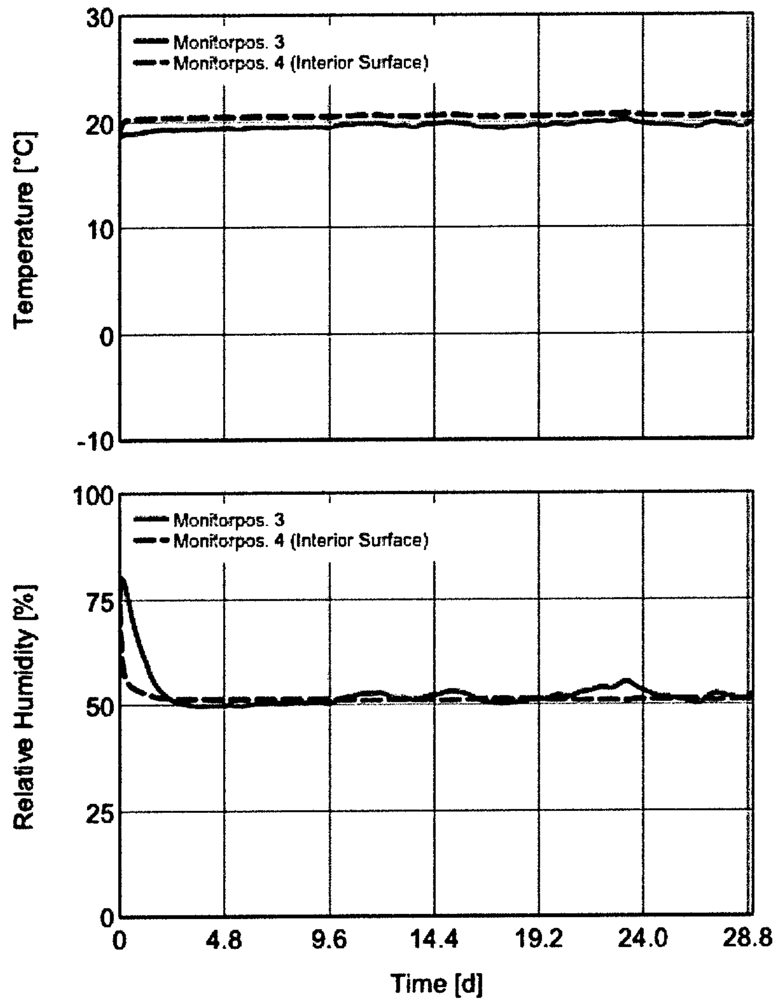
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]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Monitorpos. 4 (Interior Surface)
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0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
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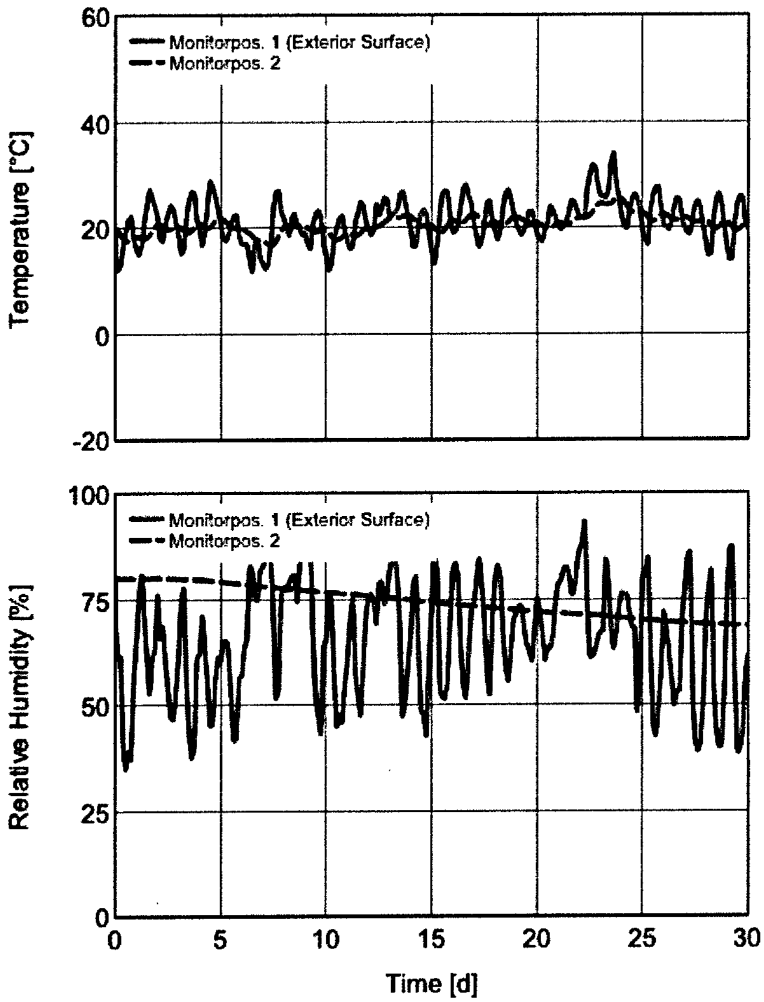
Relative Humidity [%]
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



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40
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-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
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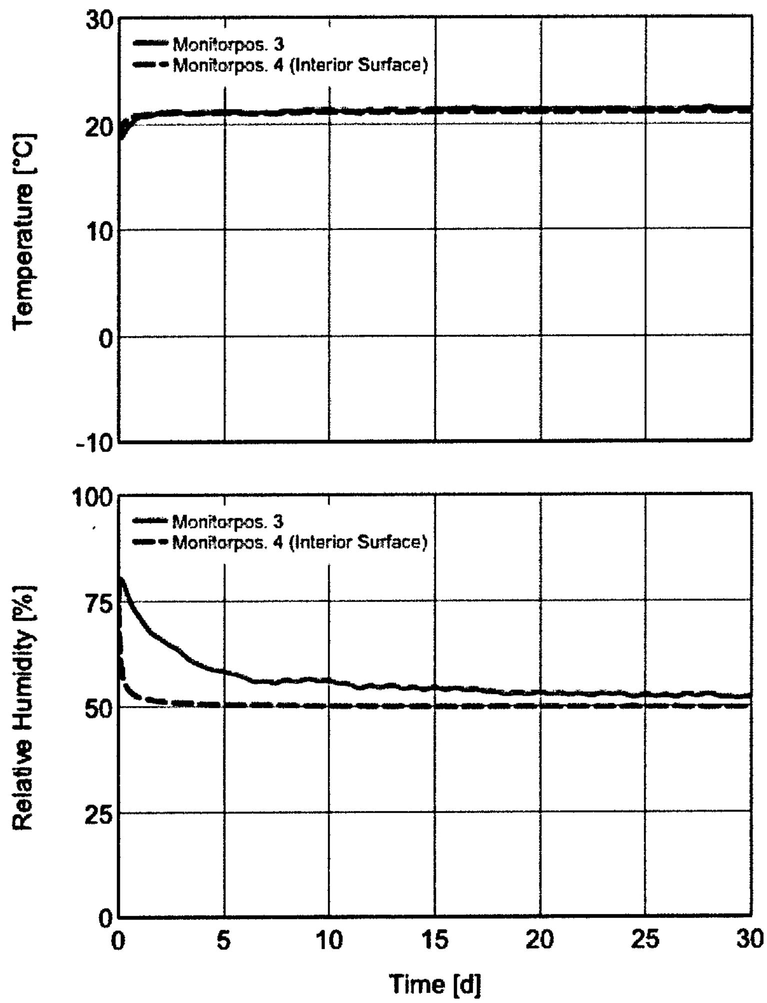
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]



Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
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20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
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0
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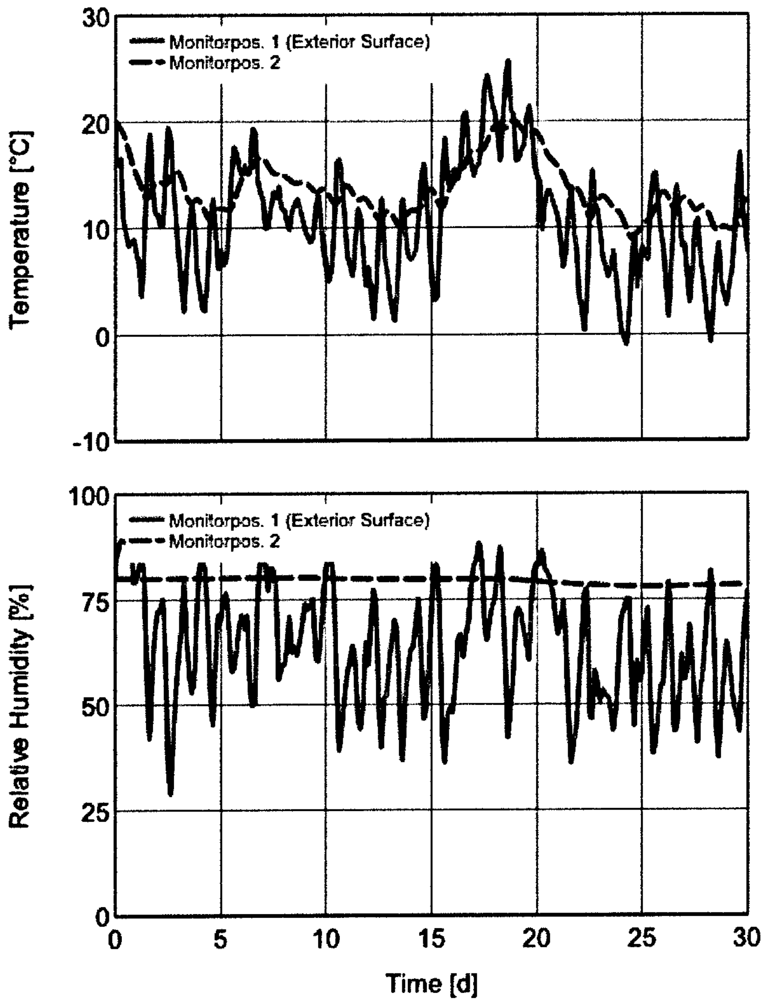
10
15
20
25
30
Time [d]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Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
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75
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Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
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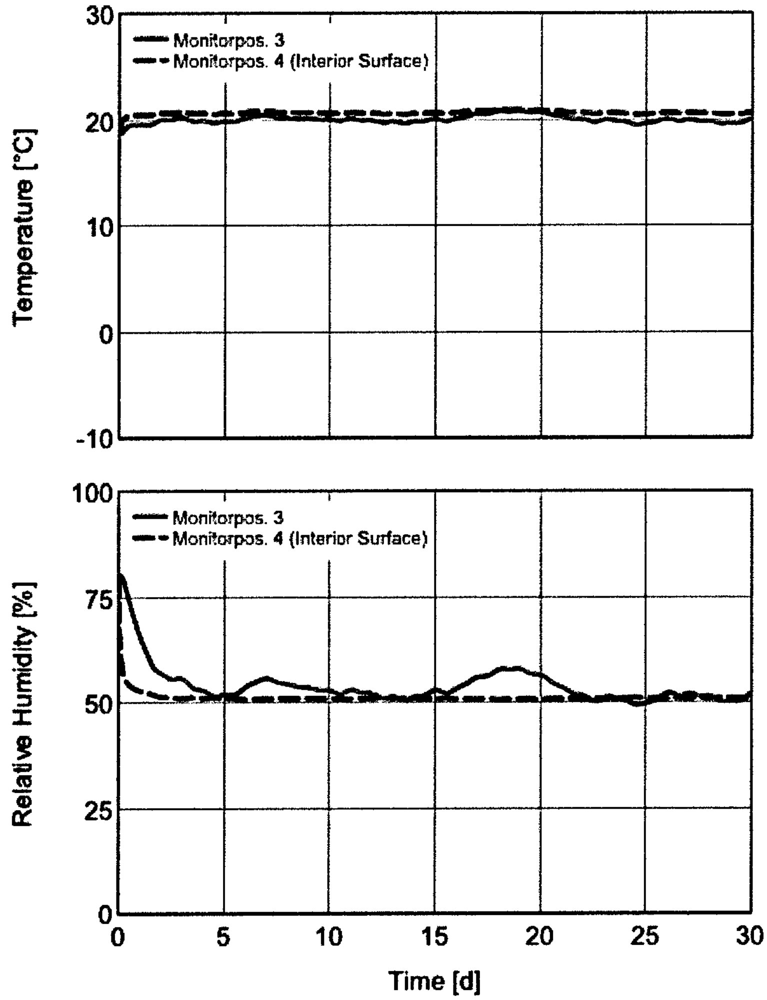
10
15
20
25
30
Time [d]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Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
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75
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Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
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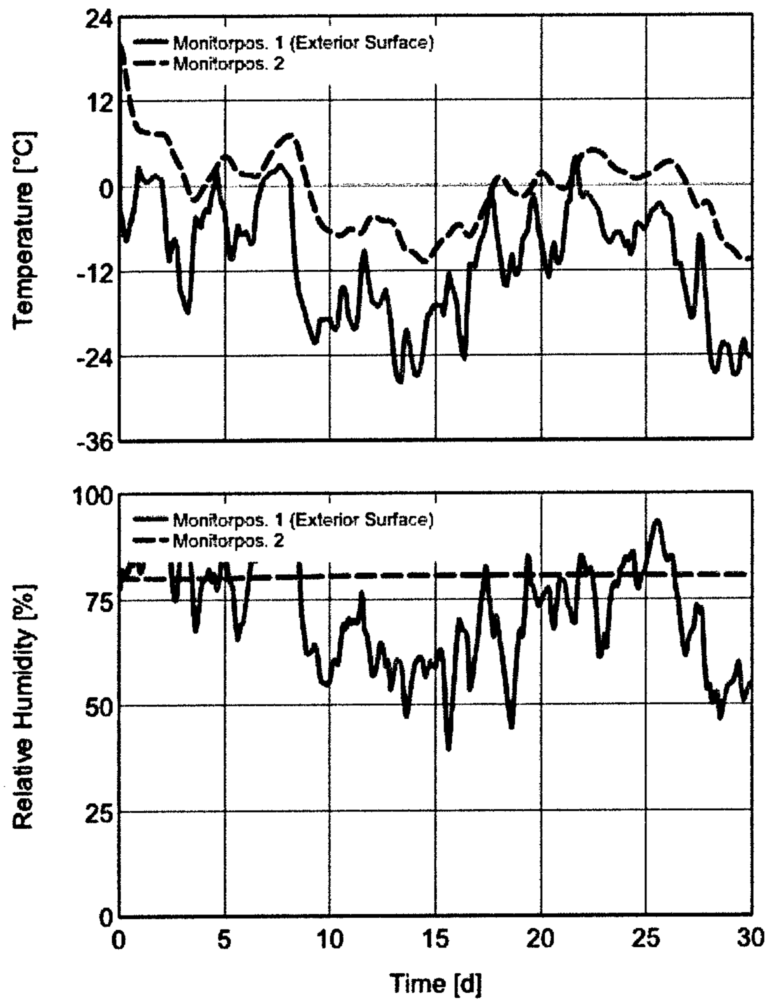
10
15
20
25
30
Time [d]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-24
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Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
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75
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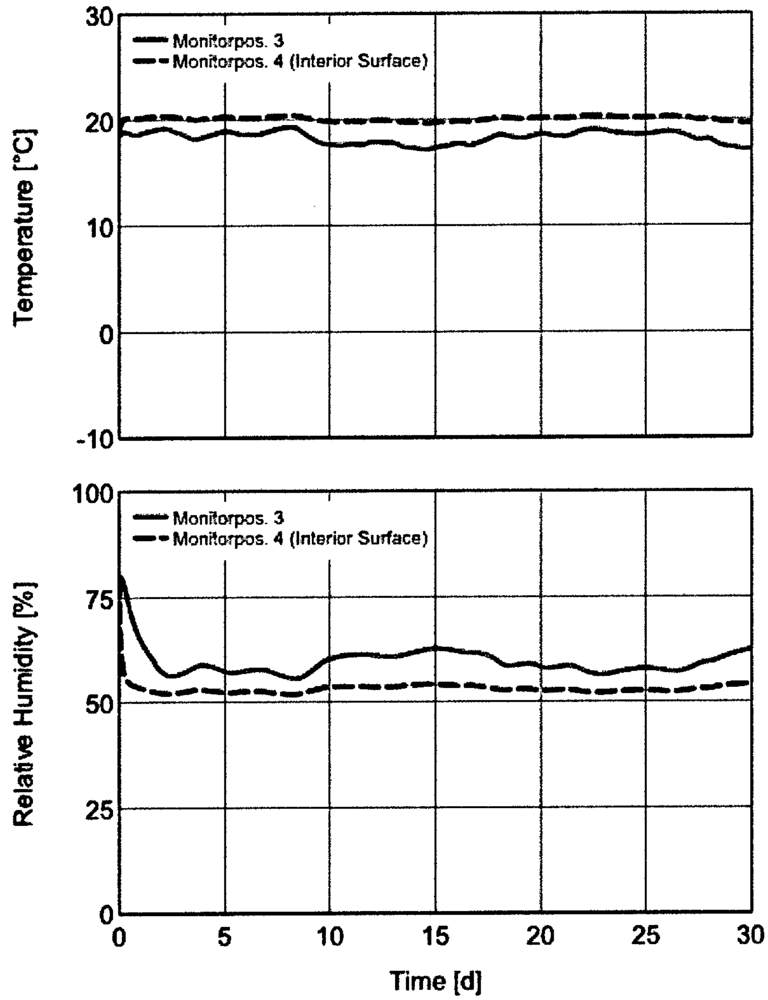
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]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Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
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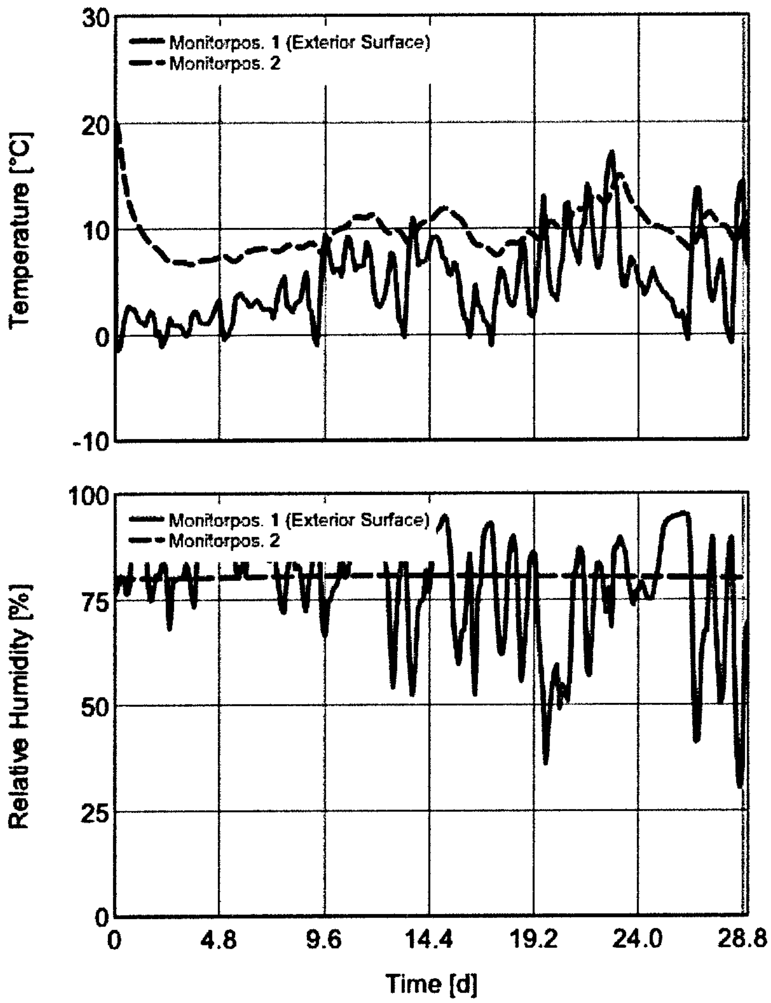
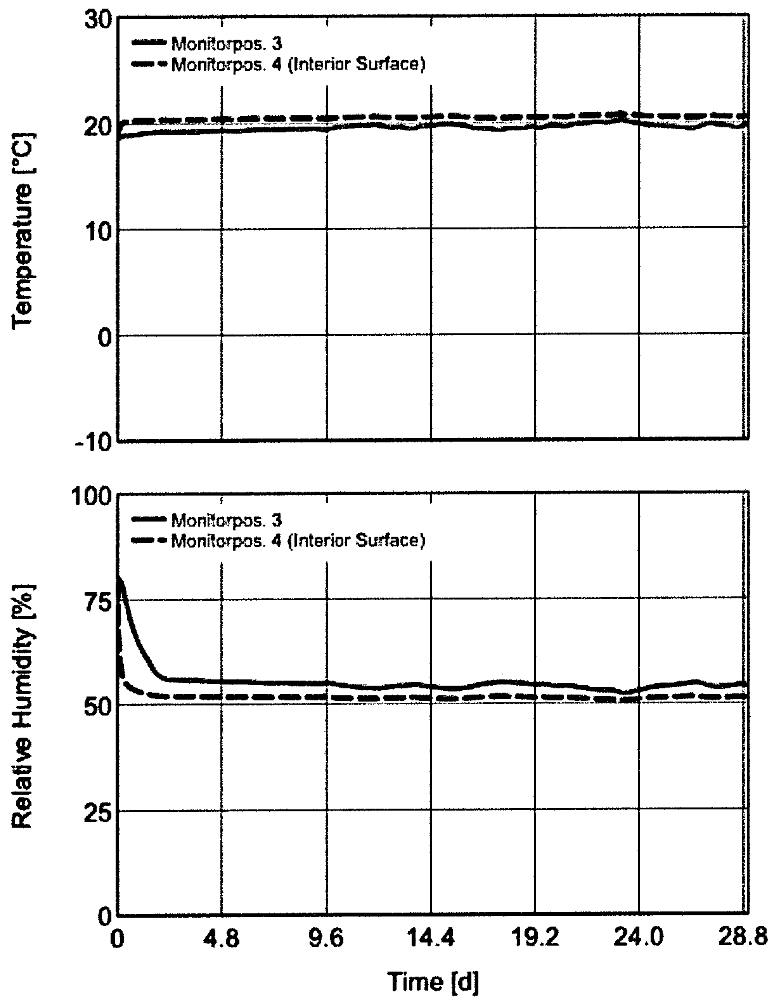
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]



Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
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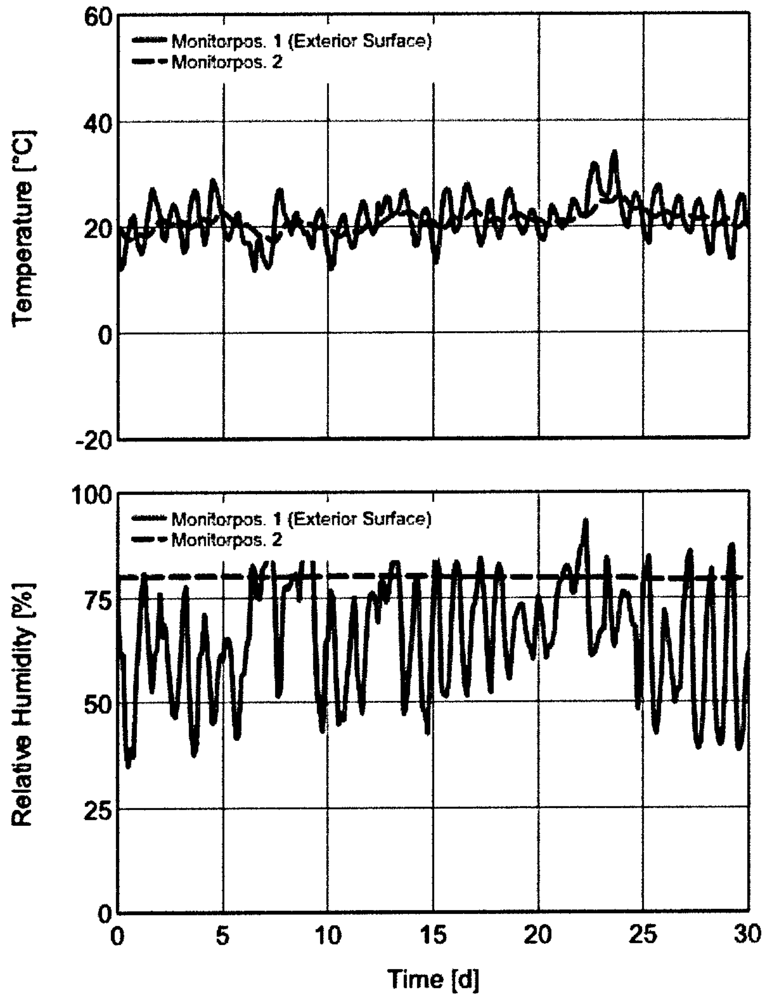
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]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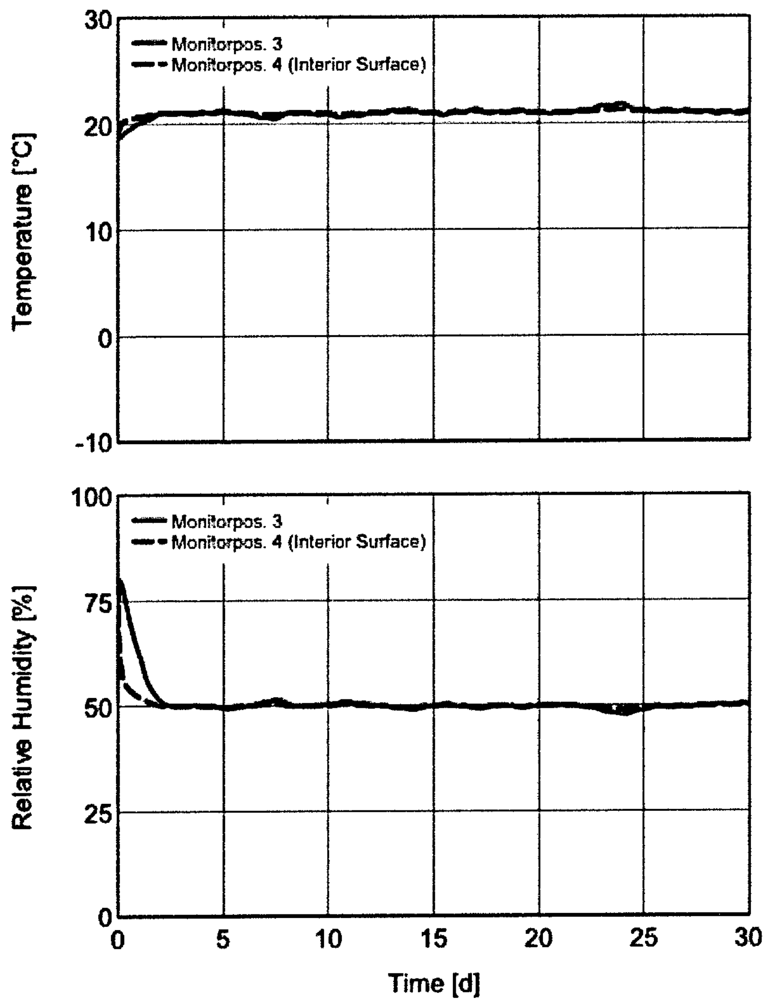
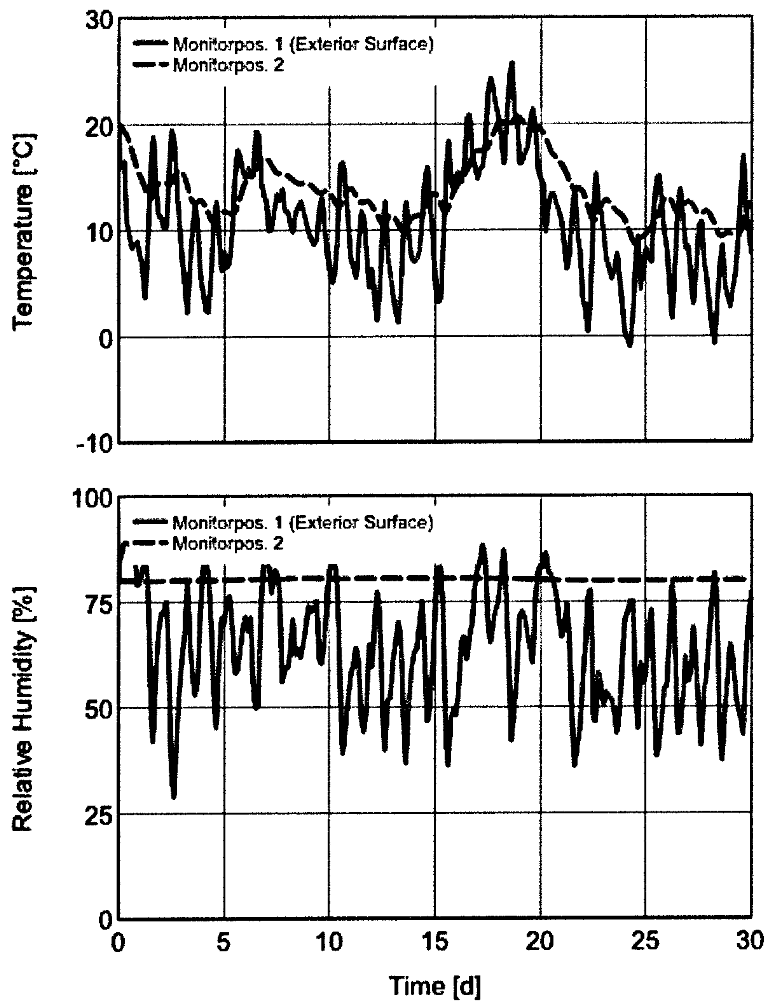
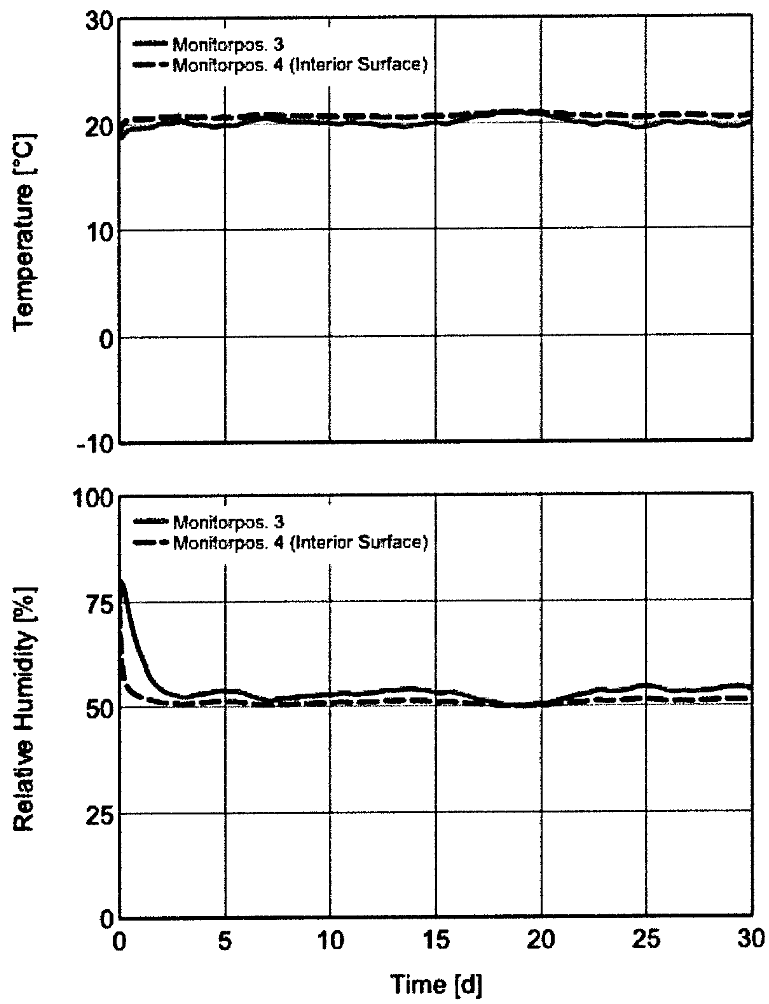
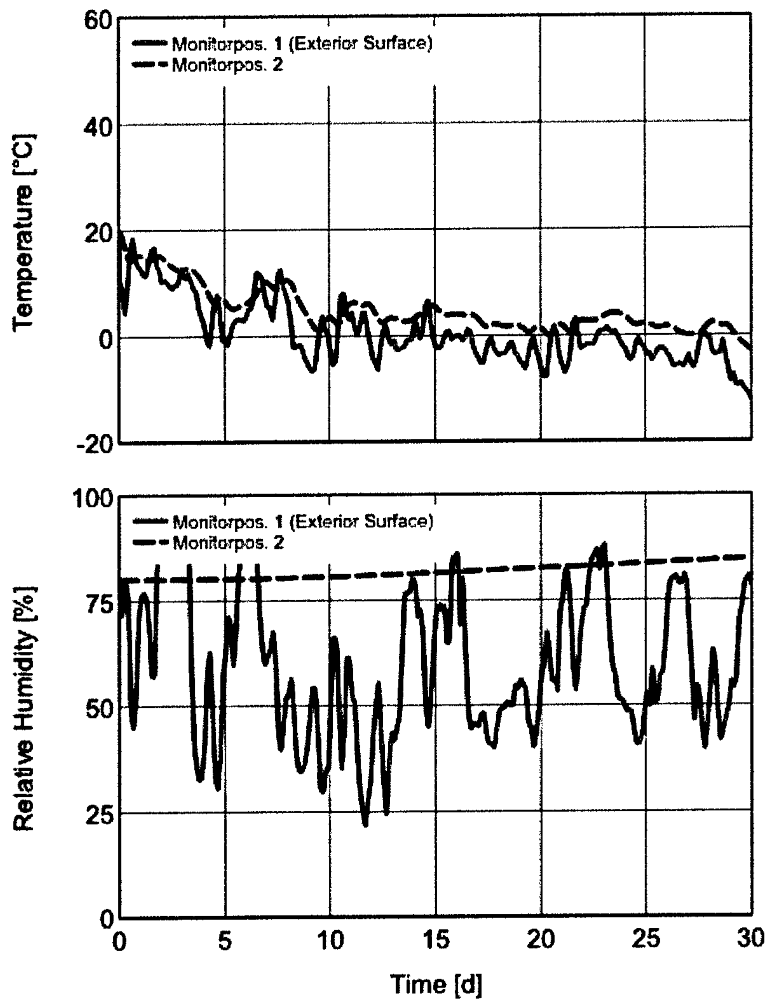
20
0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]


Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]

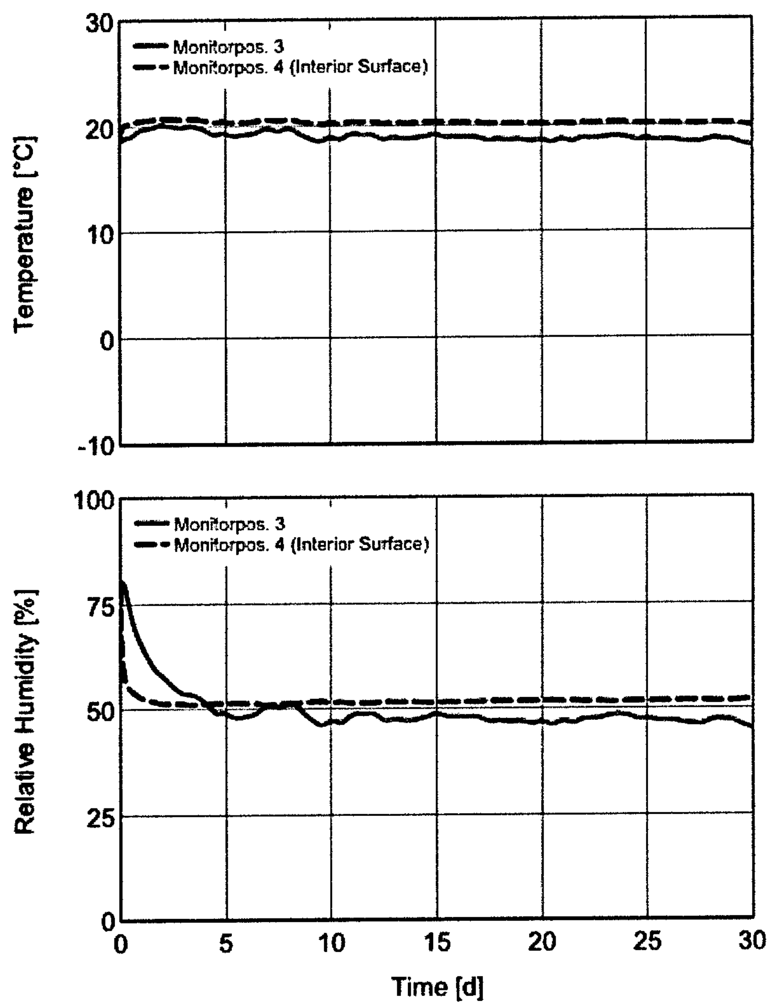

Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]


Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]

Appendix 3 – Roanoke Test Data



60
40
20
0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]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20
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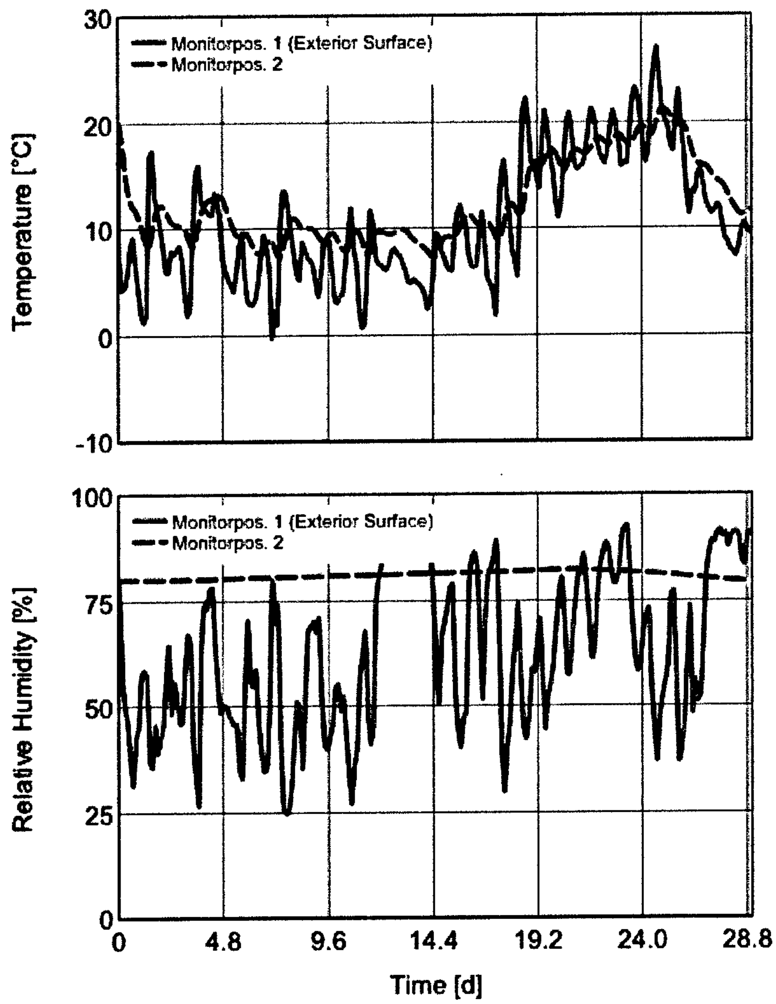
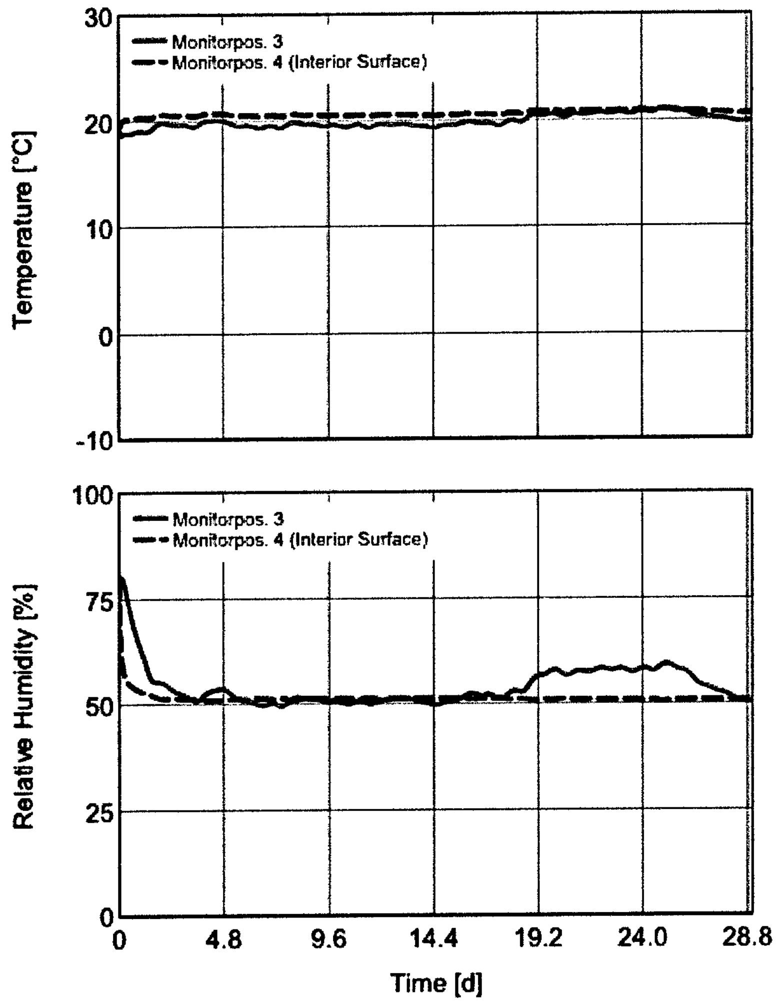
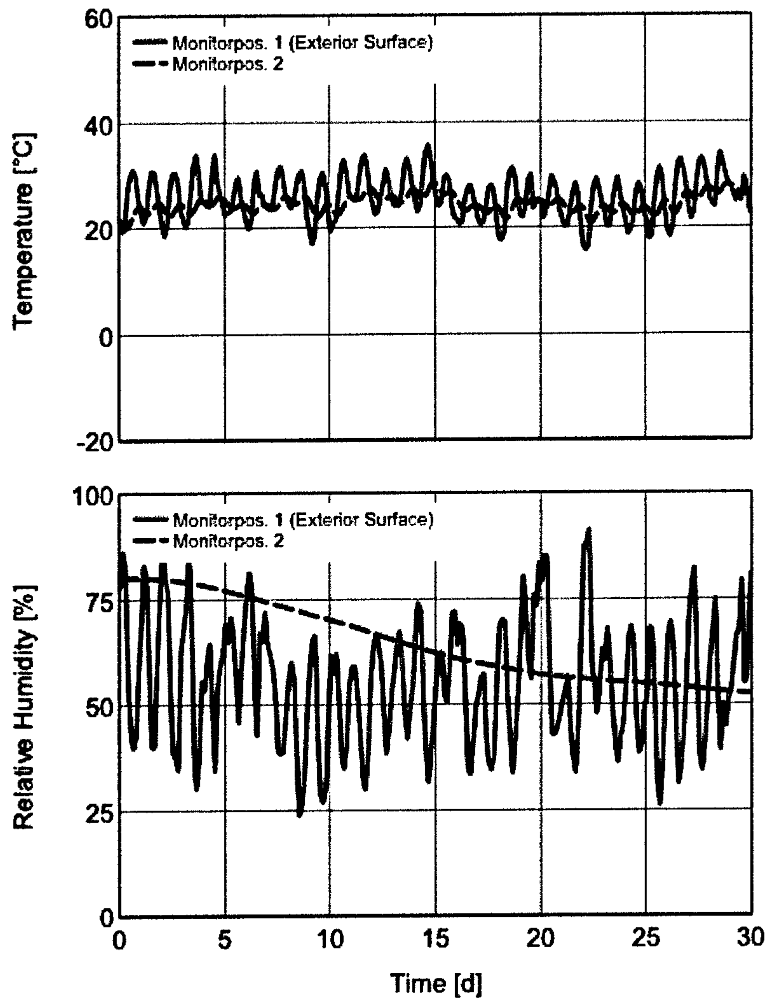
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]


Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]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40
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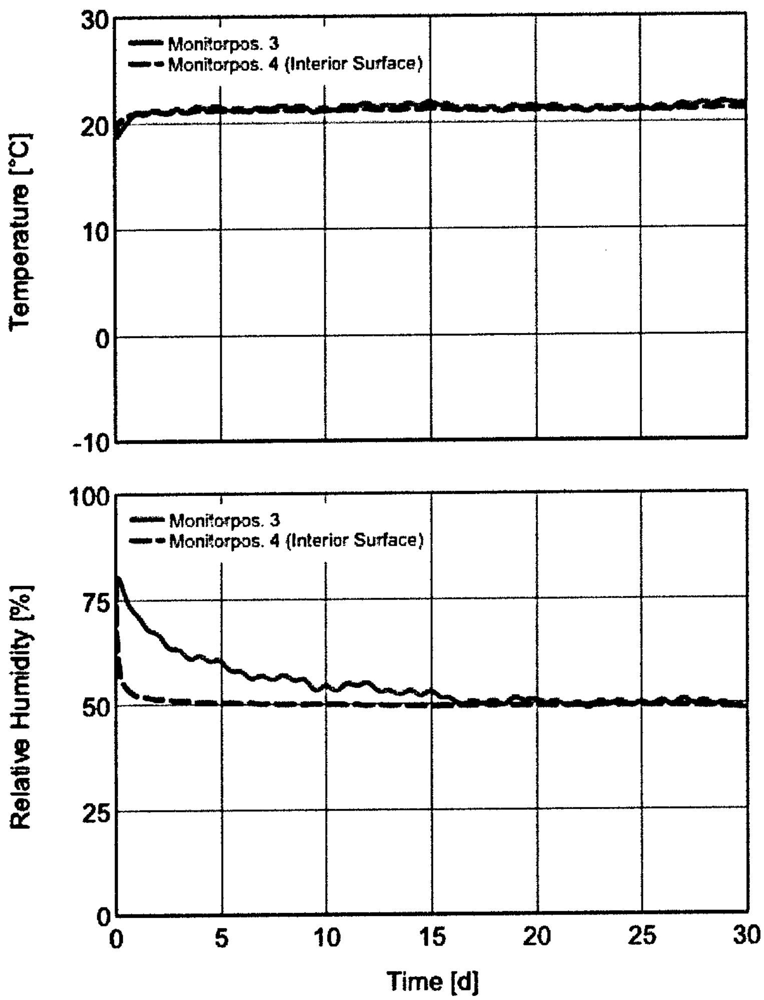
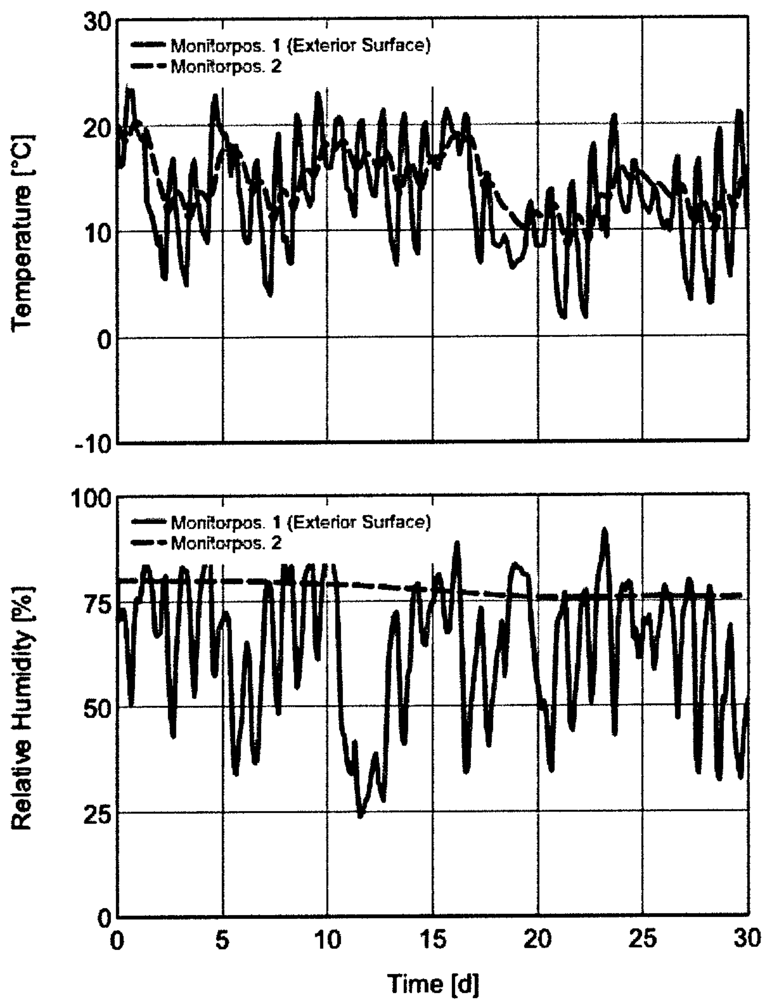
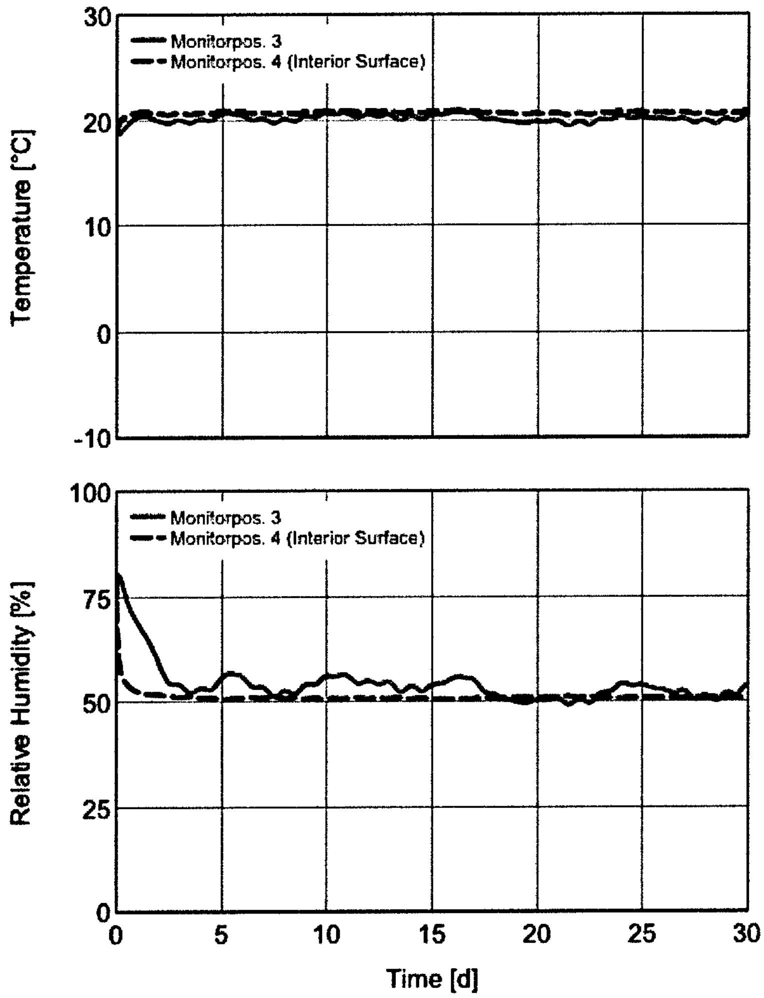
0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]

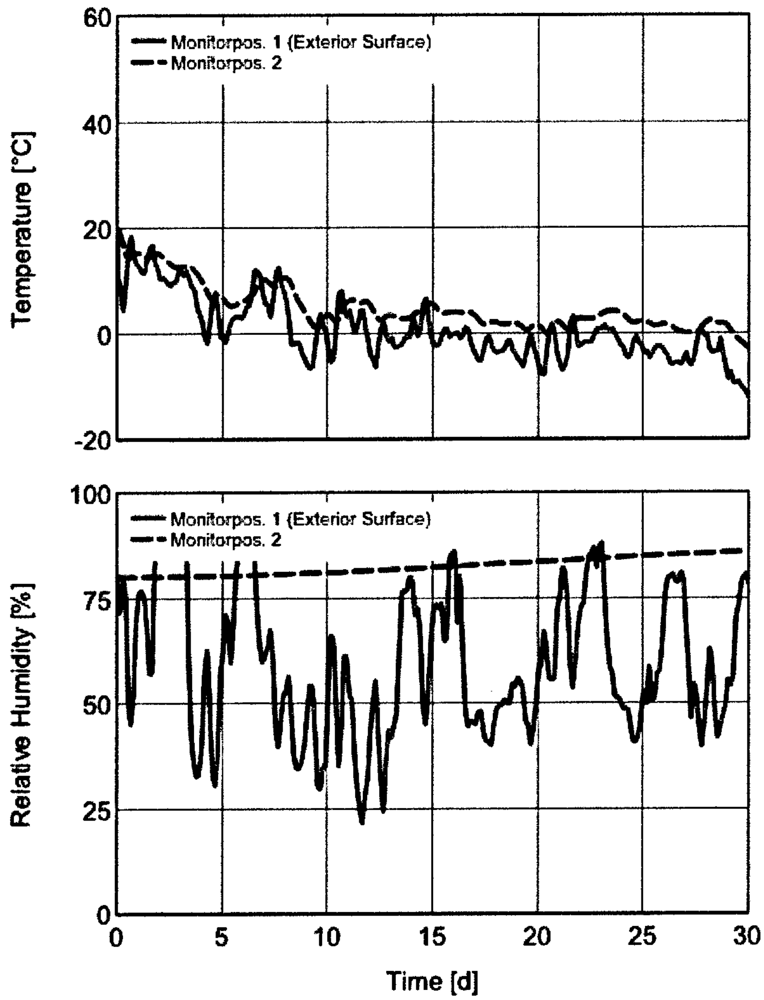

Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]



Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
Time [d]



30
20
10
0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]


60
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20
0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
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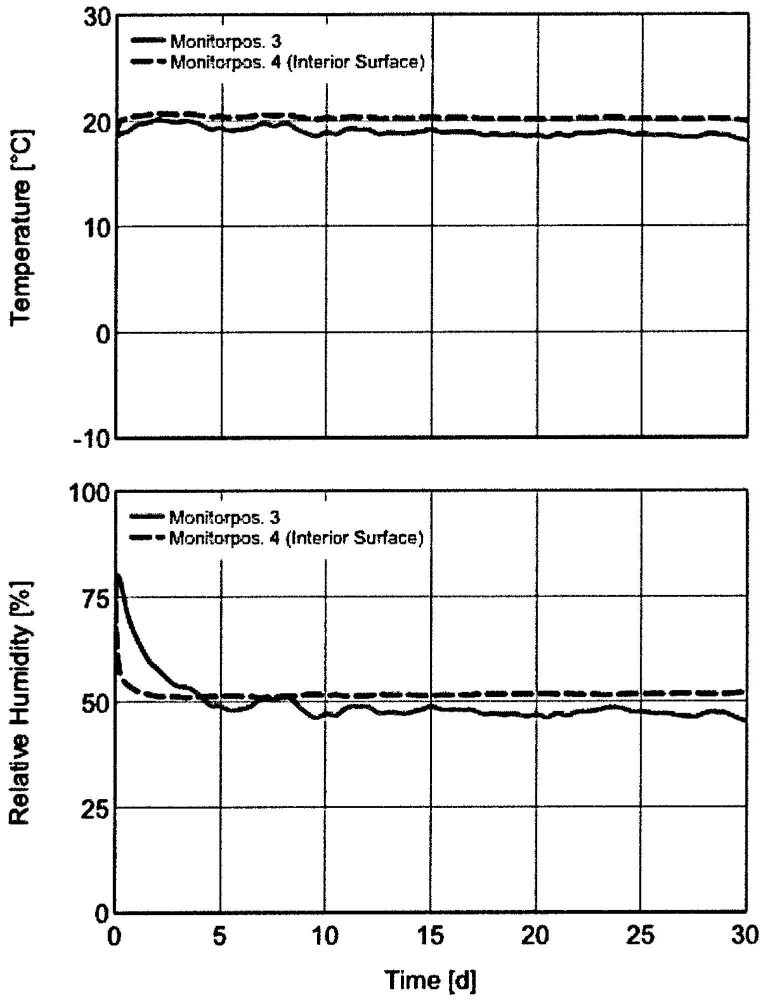
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]


Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
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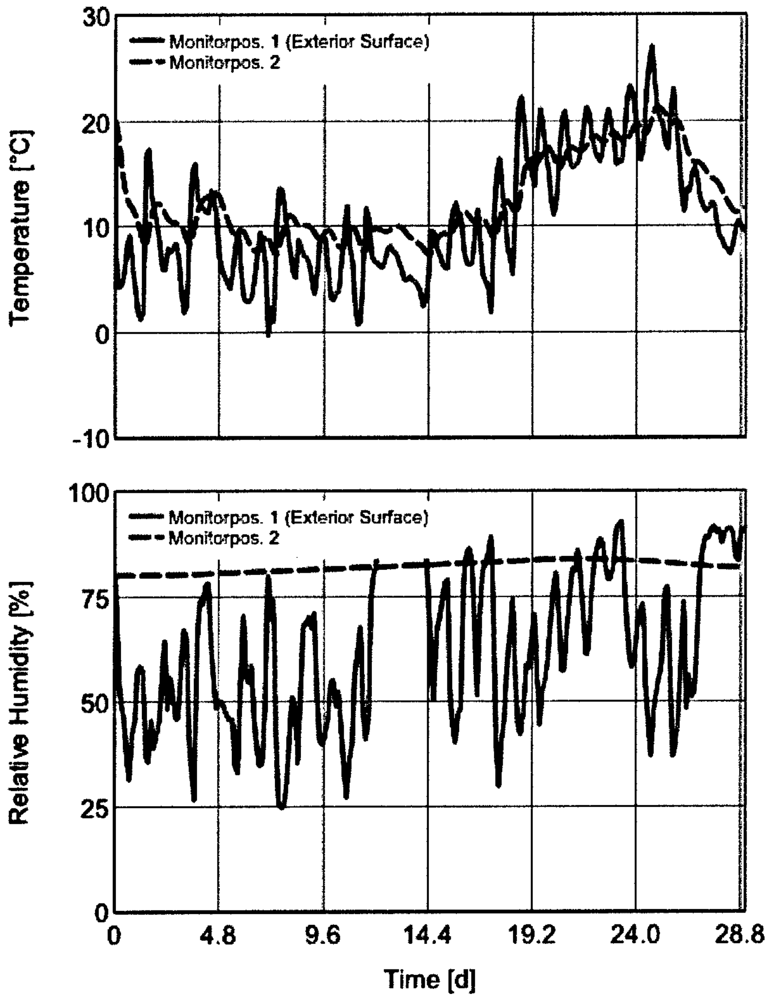
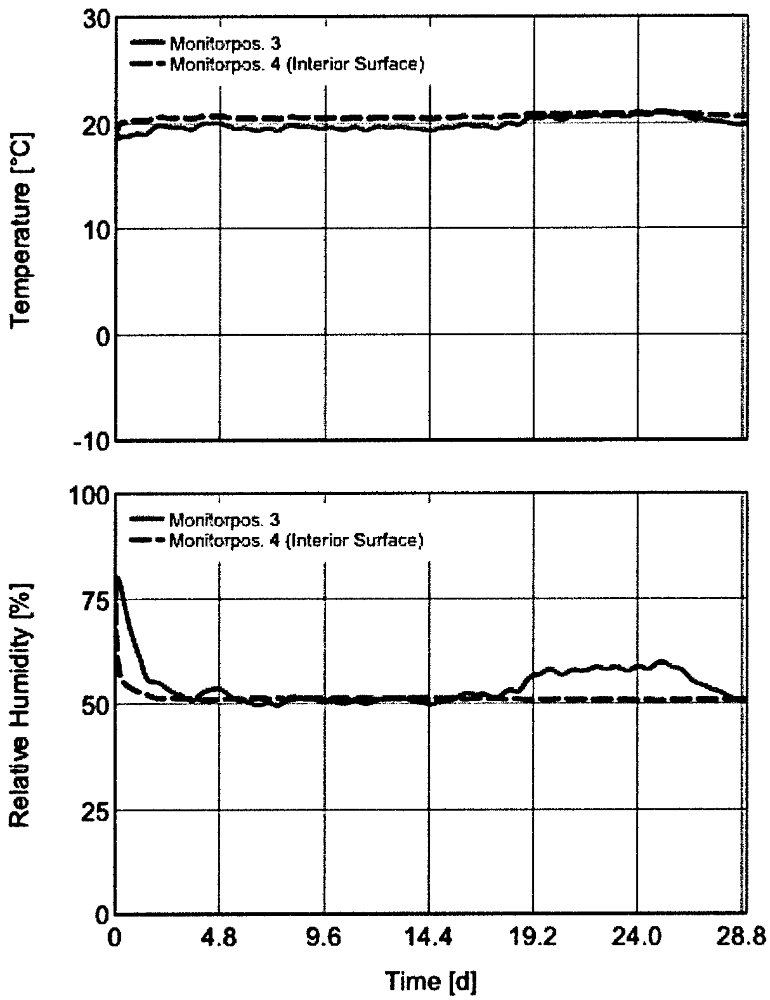
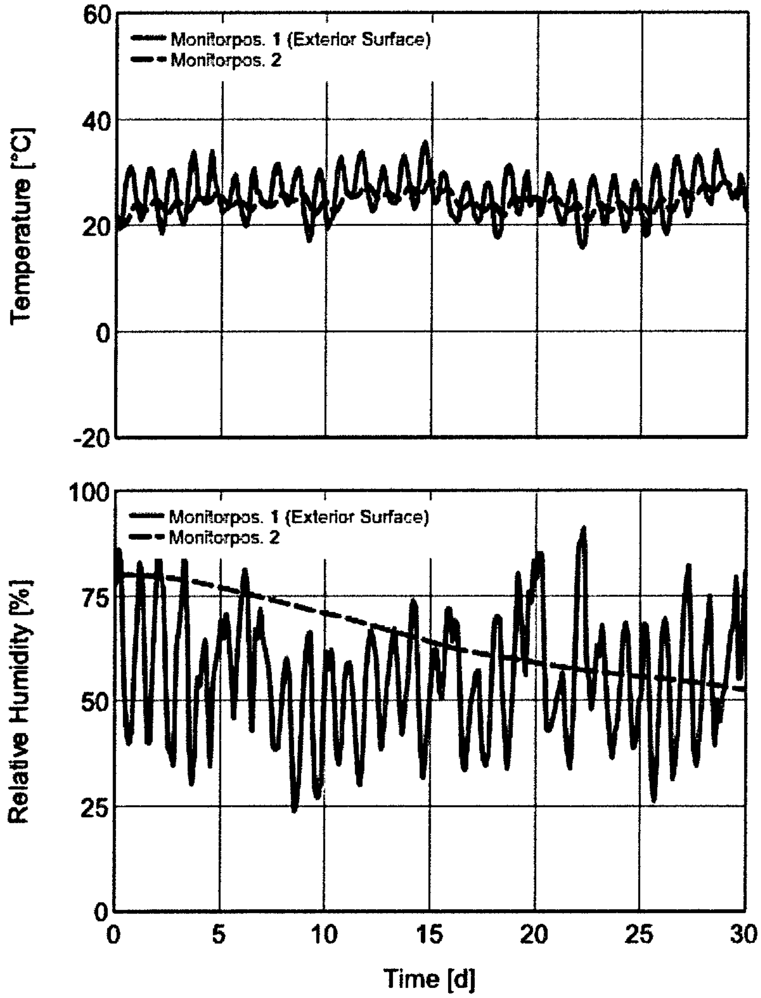
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]



Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



Project: Project and Report / Case 1: Brick Veneer Model - 1-VB-R-4-AC (New Orleans VB Location)



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20
0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
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25
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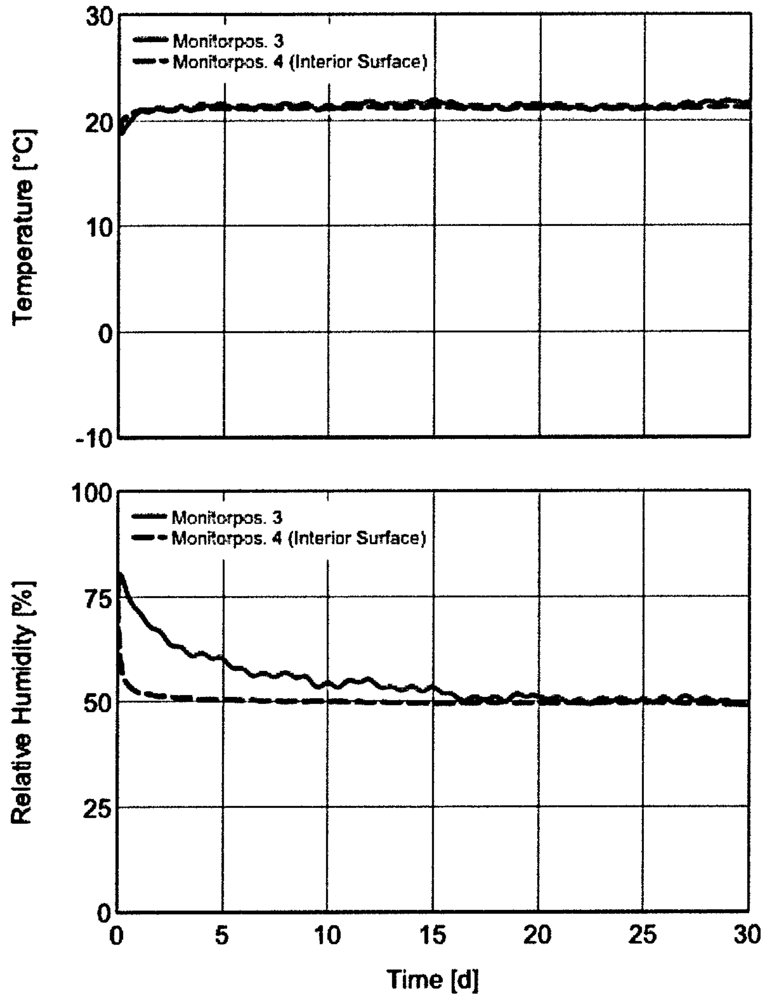
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]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0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
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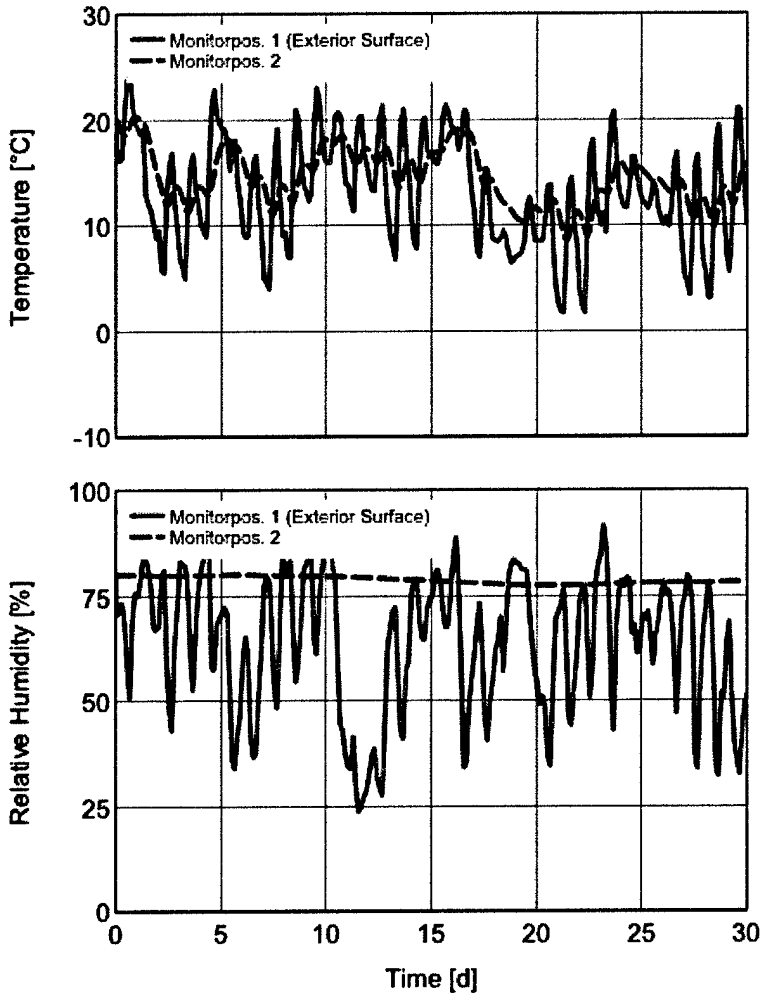
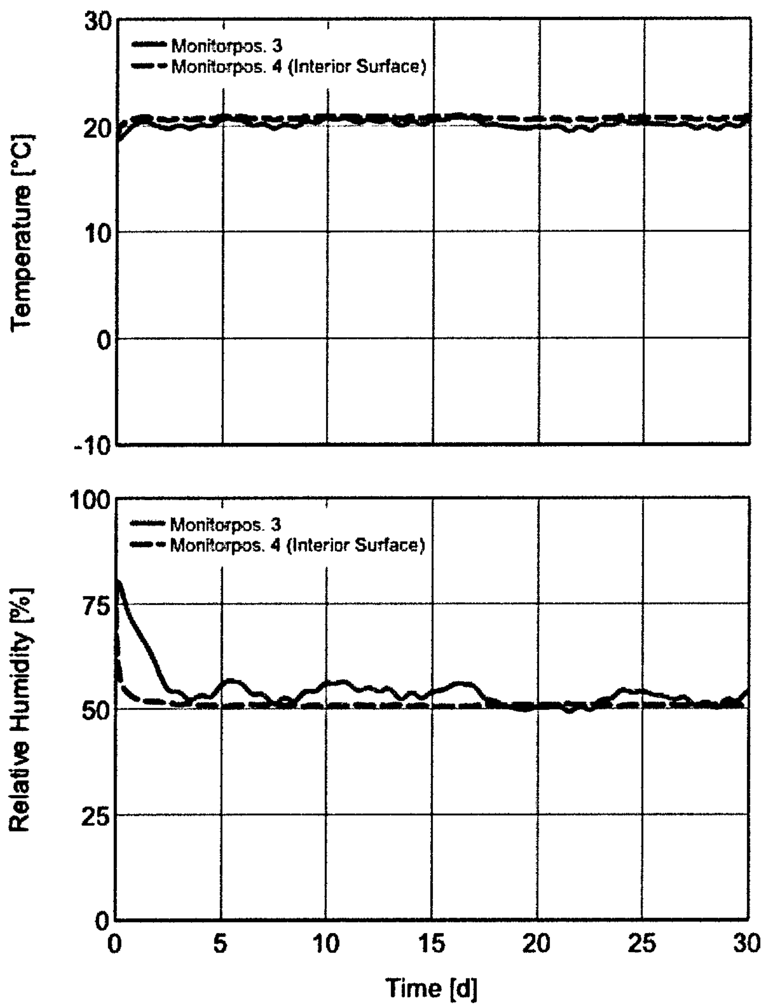
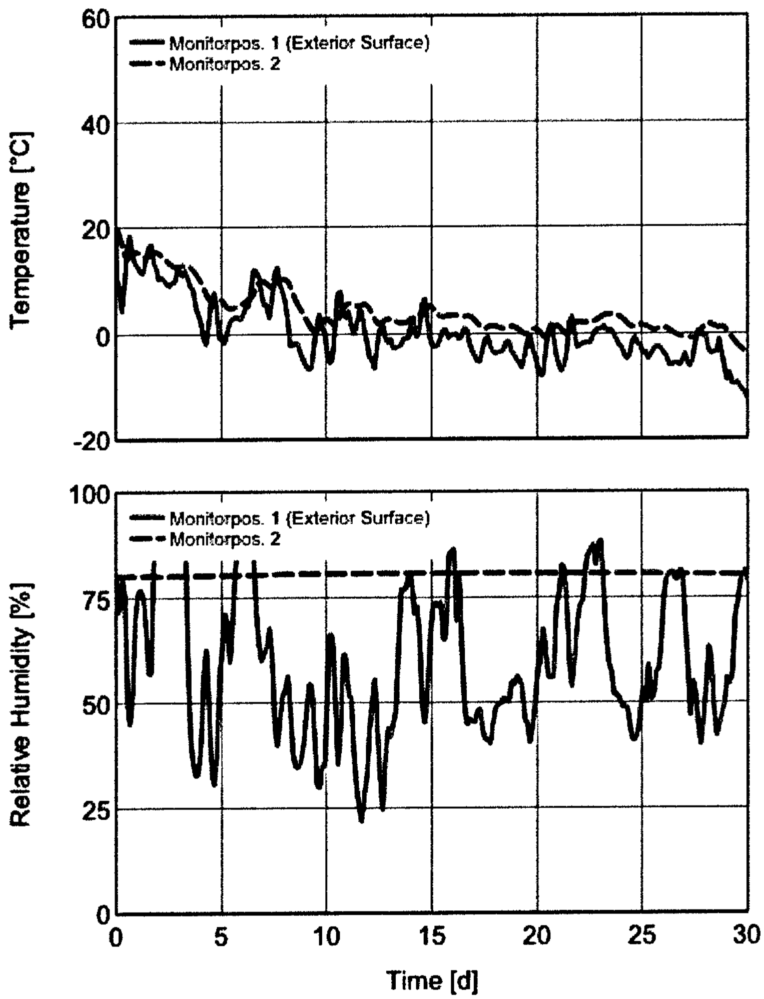
25
0
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]



Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
30
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]



Project: Project and Report / Case 1: Brick Veneer Model - 1-VB-R-10-AC (New Orleans VB Location)



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0
-20
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
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75
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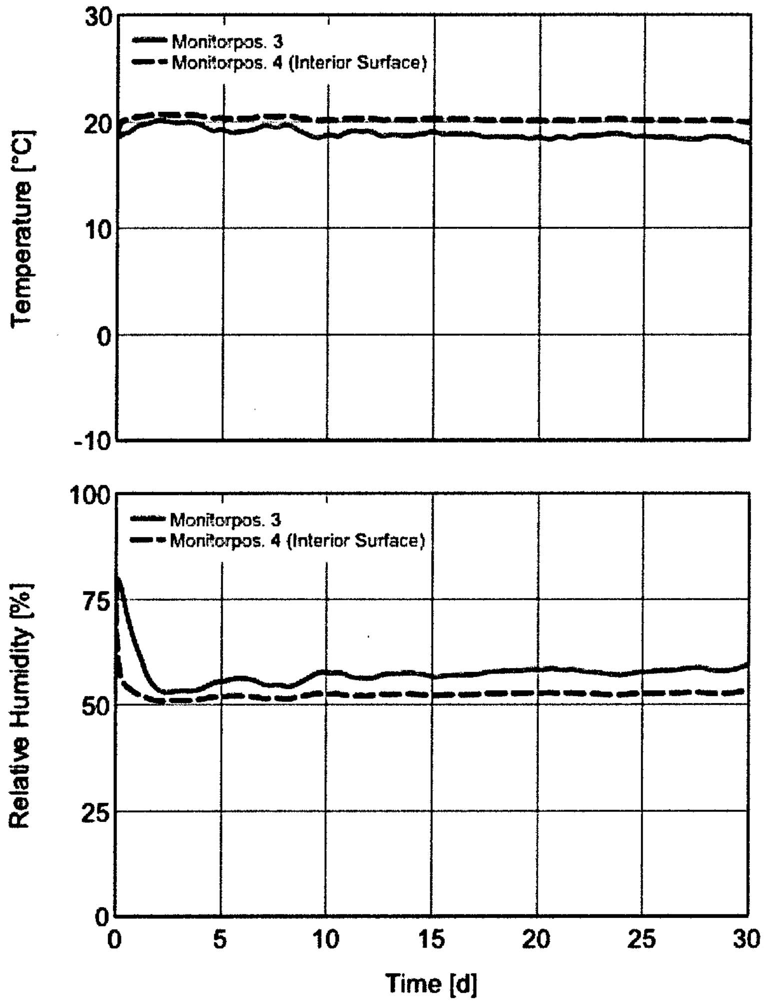
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]



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0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
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75
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Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
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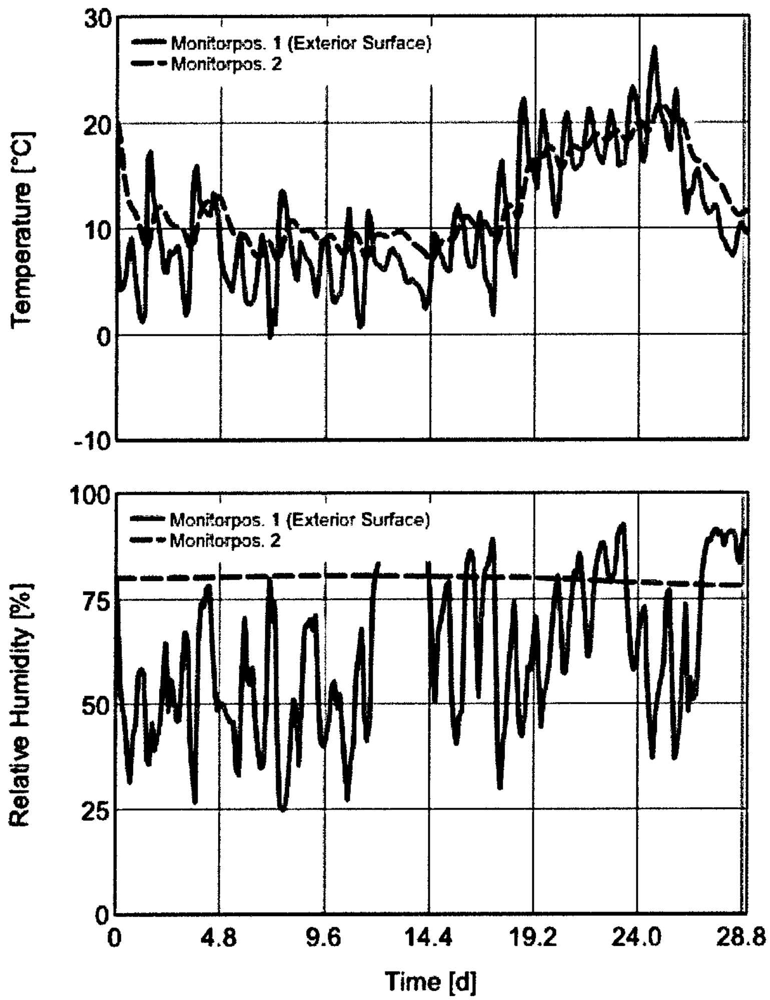
5
10
15
20
25
30
Time [d]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0
-10
Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
100
75
50
25
0
Relative Humidity [%]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
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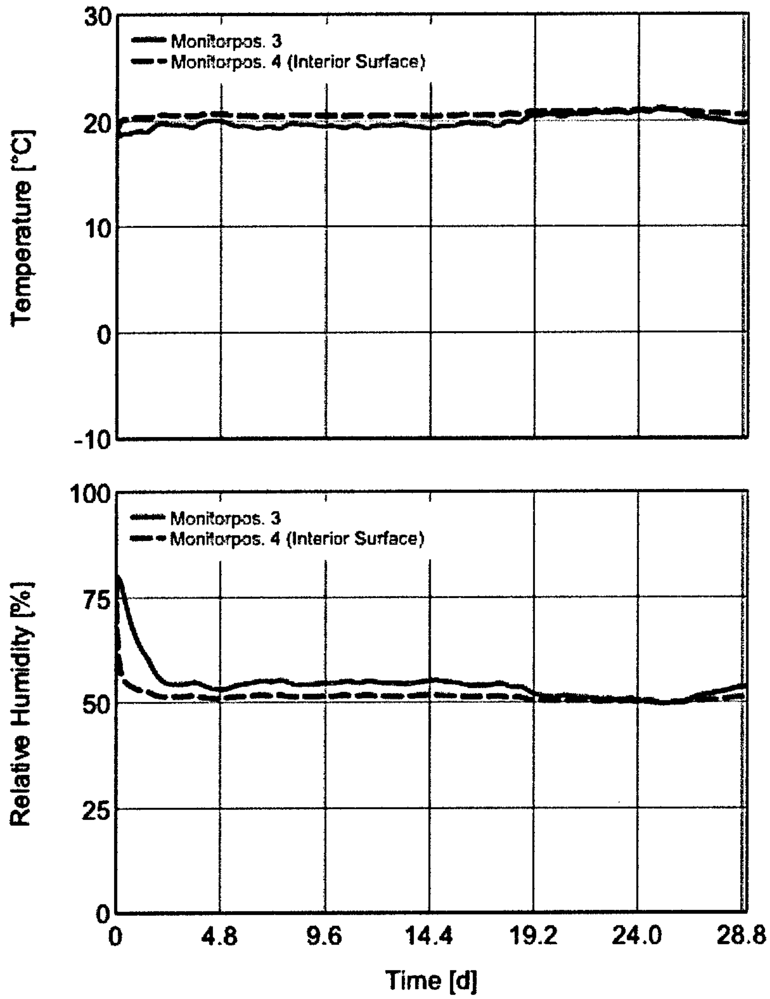
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]



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0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
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75
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25
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Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
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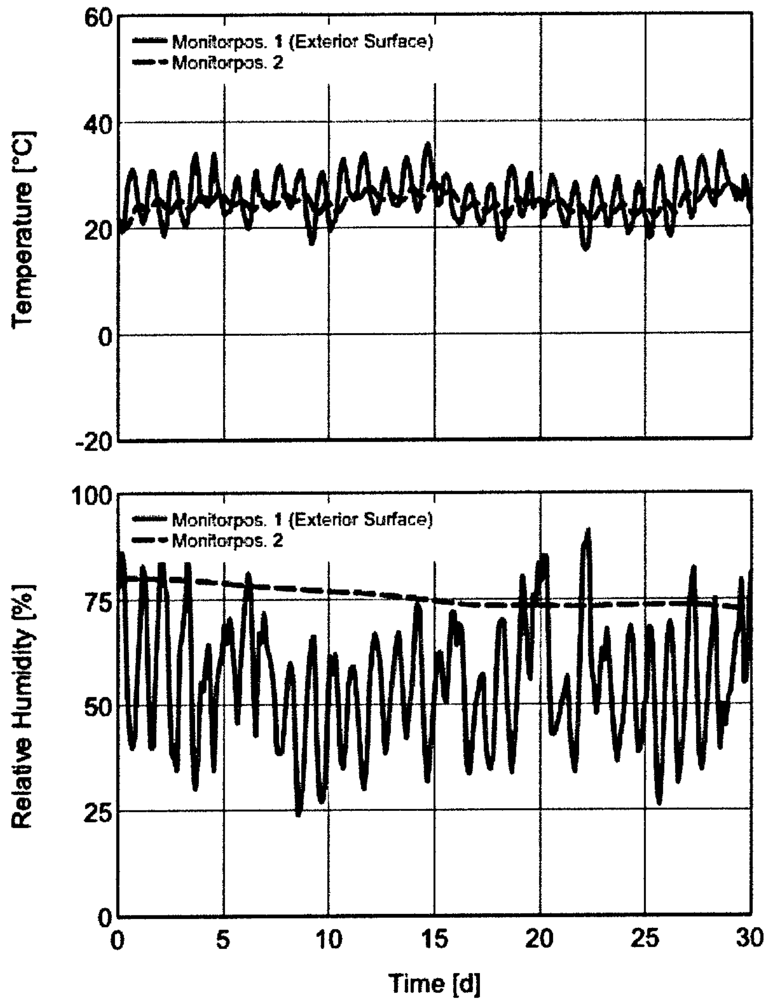
4.8
9.6
14.4
19.2
24.0
28.8
Time [d]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Temperature [°C]
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
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75
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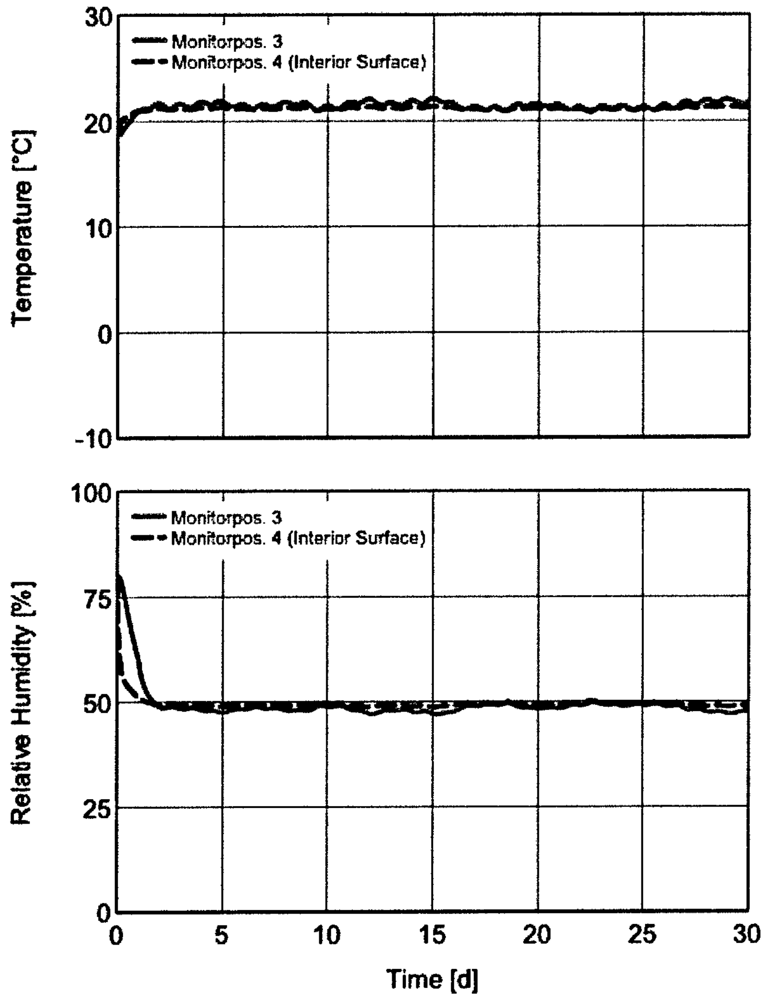
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
0
5
10
15
20
25
30
Time [d]



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0
-10
Temperature [°C]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
100
75
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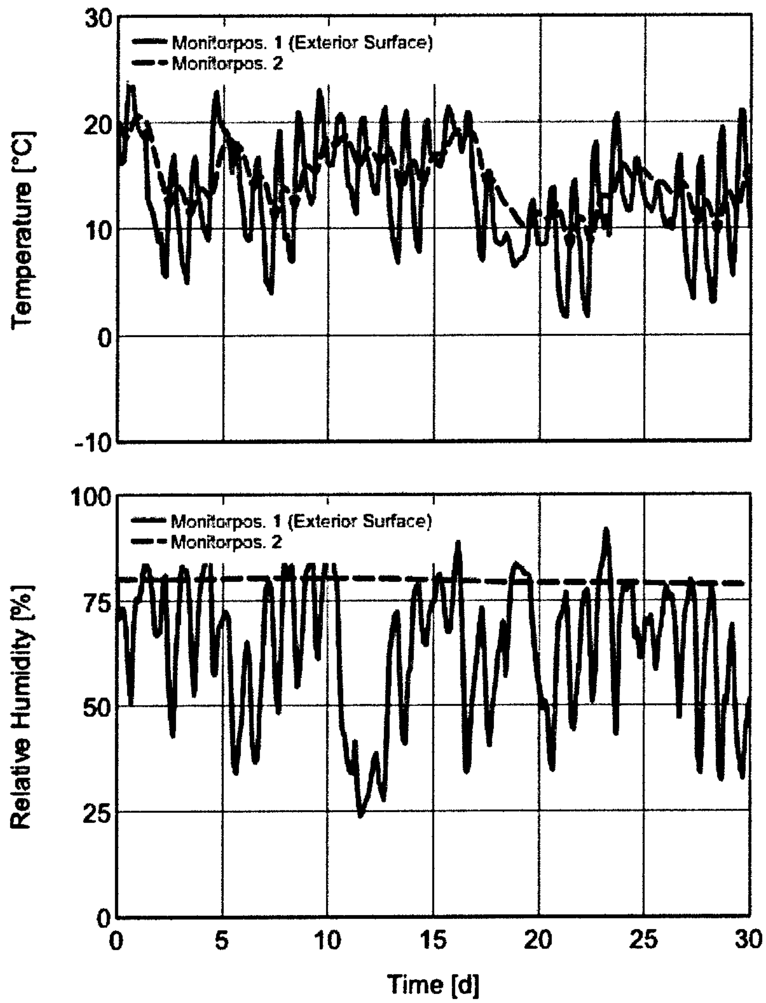
Relative Humidity [%]
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
0
5
10
15
20
25
30
Time [d]



Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Temperature [°C]
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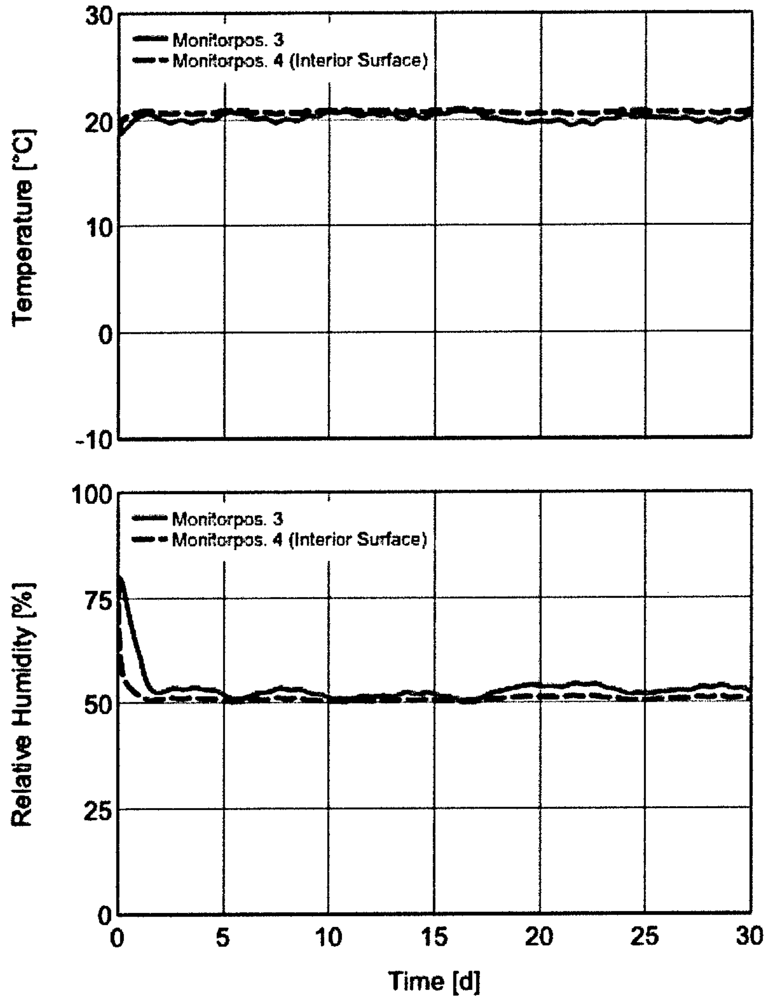
20
10
0
-10
Monitorpos. 1 (Exterior Surface)
Monitorpos. 2
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
30
Time [d]


Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Temperature [°C]
30
20
10
0
-10
Monitorpos. 3
Monitorpos. 4 (Interior Surface)
Relative Humidity [%]
100
75
50
25
0
0
5
10
15
20
25
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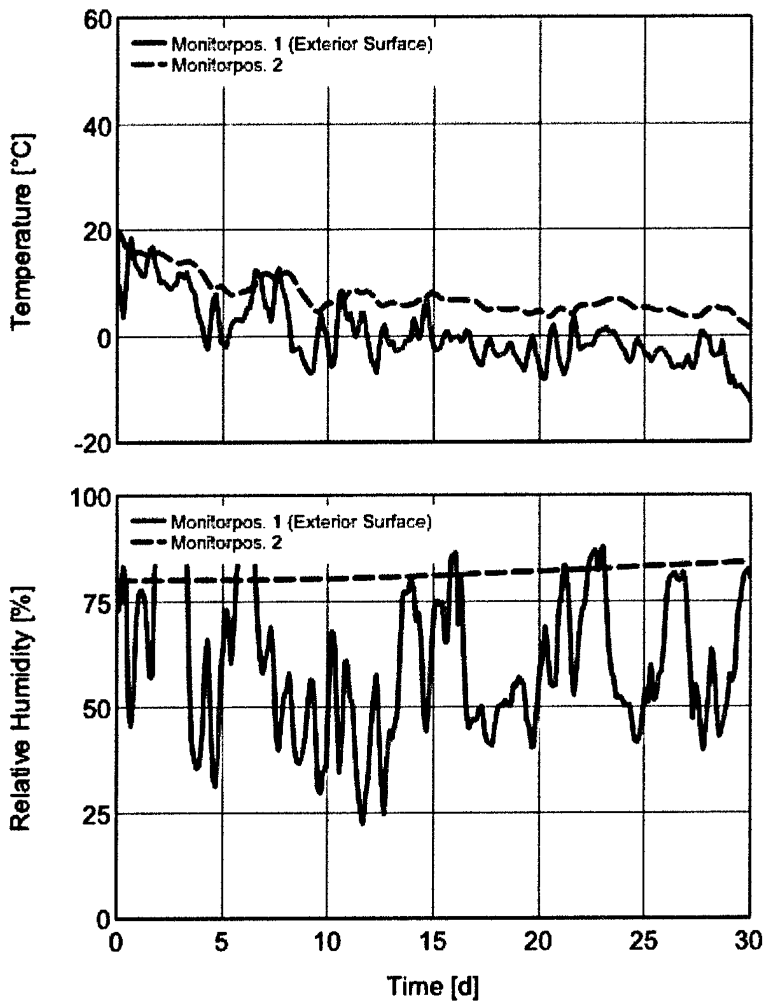
Time [d]



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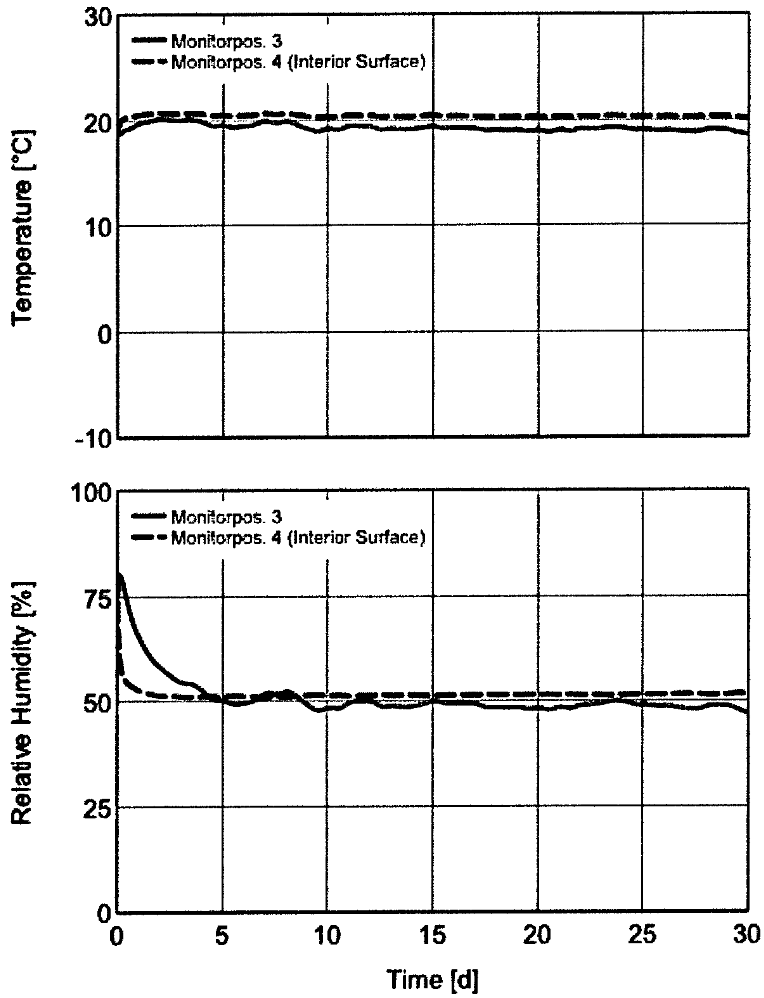

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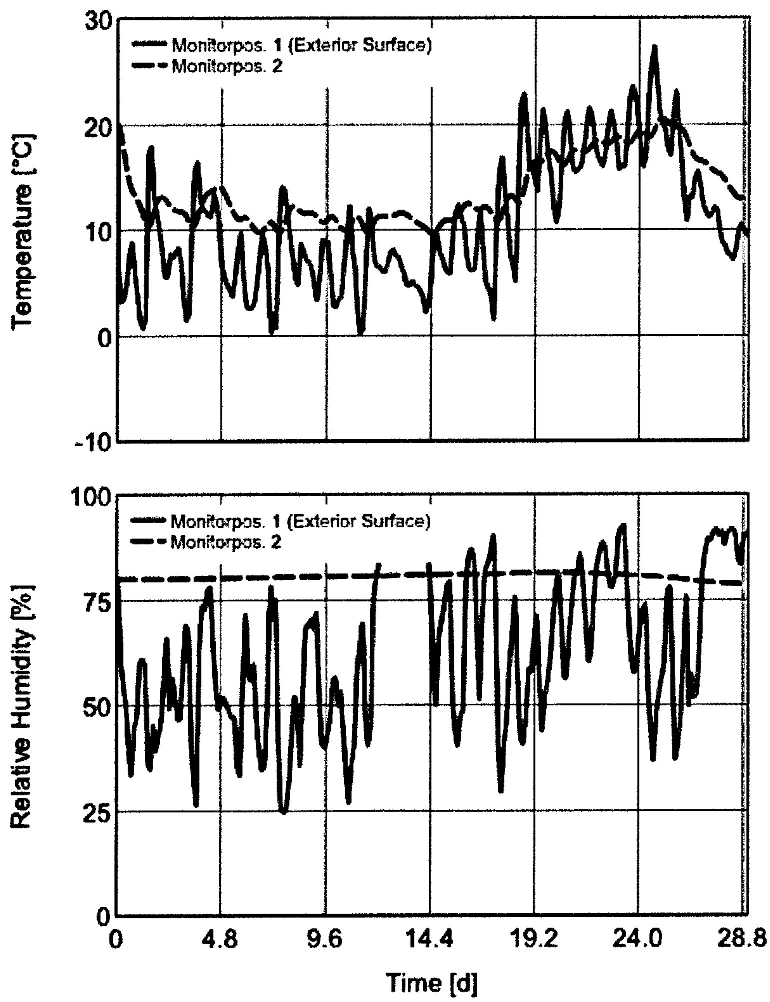

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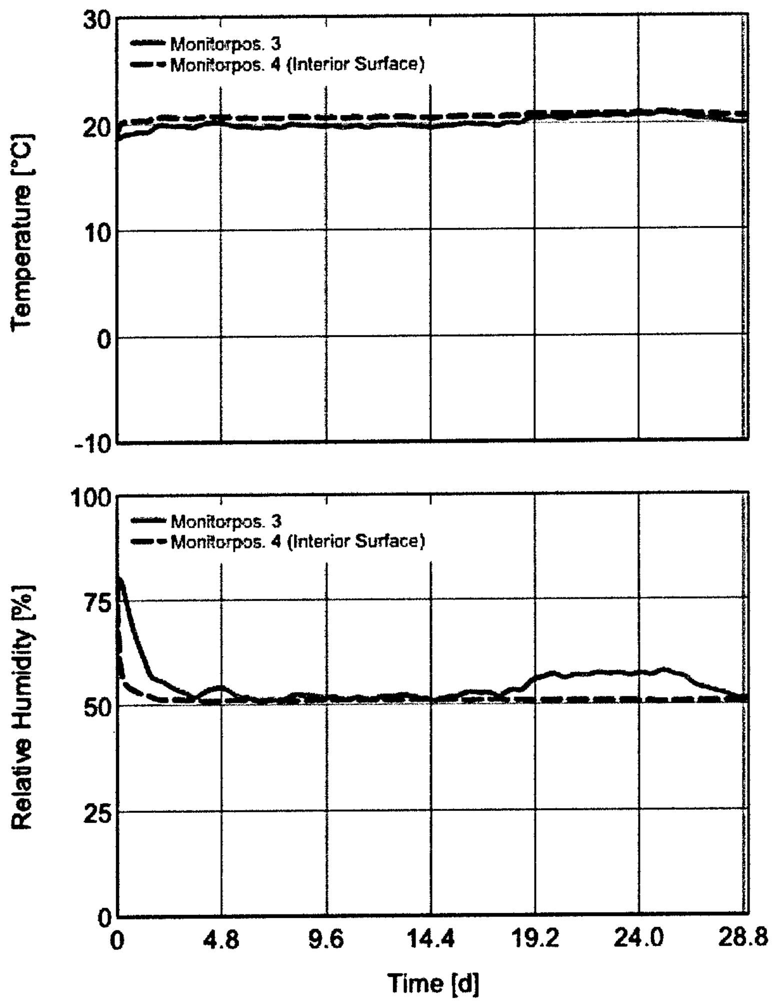

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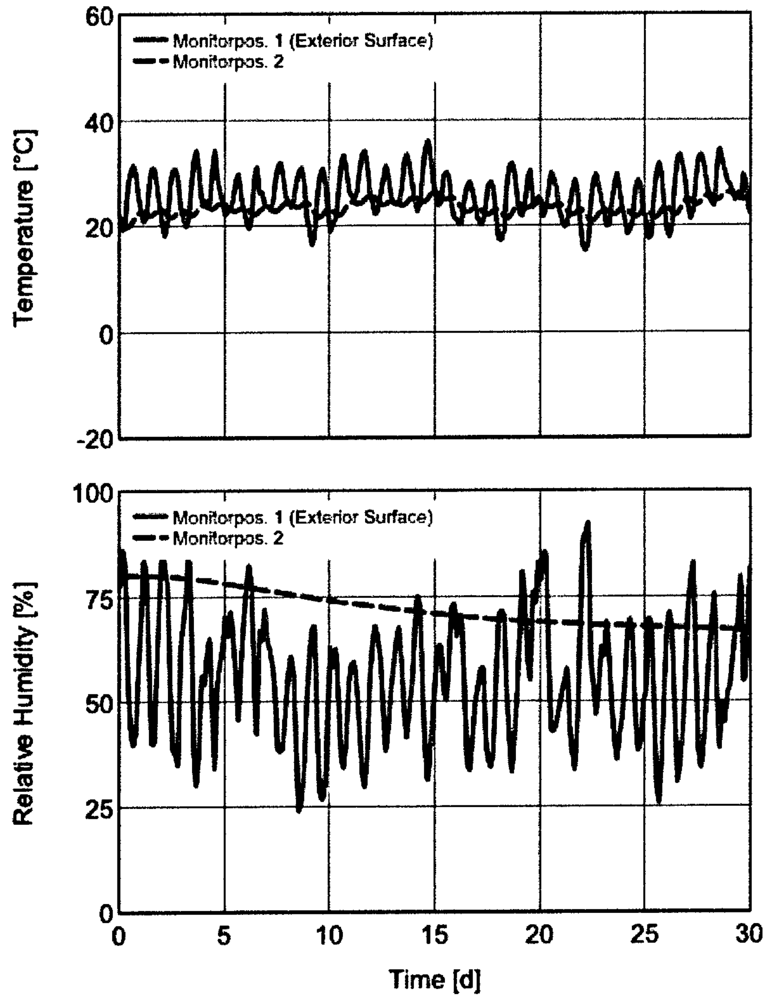
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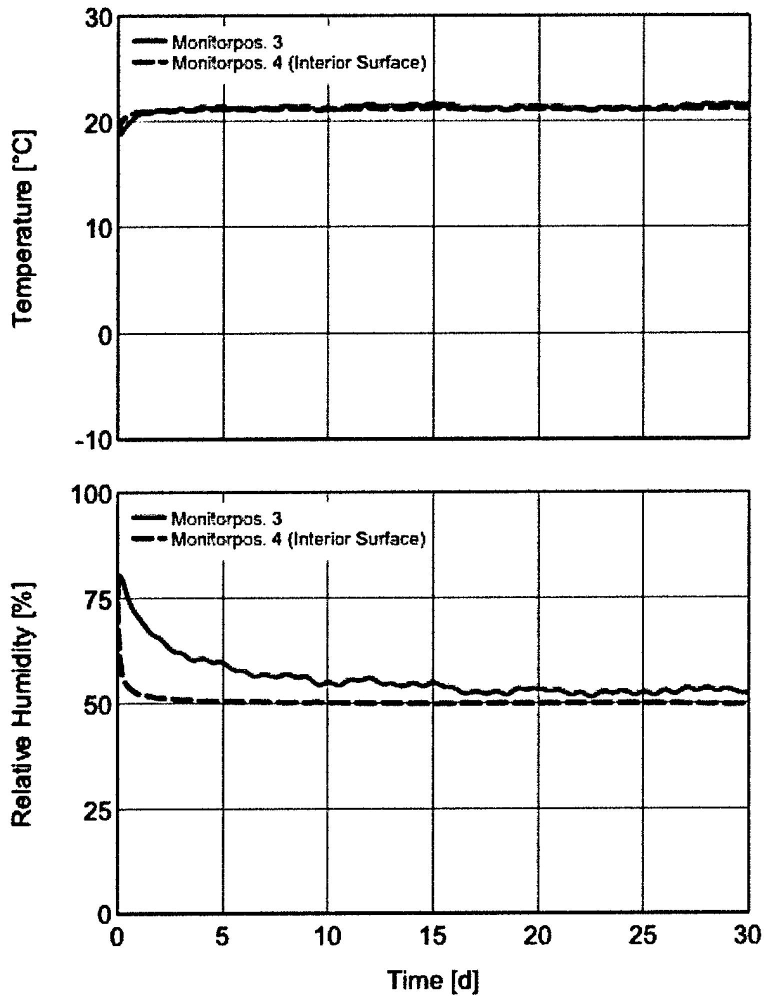
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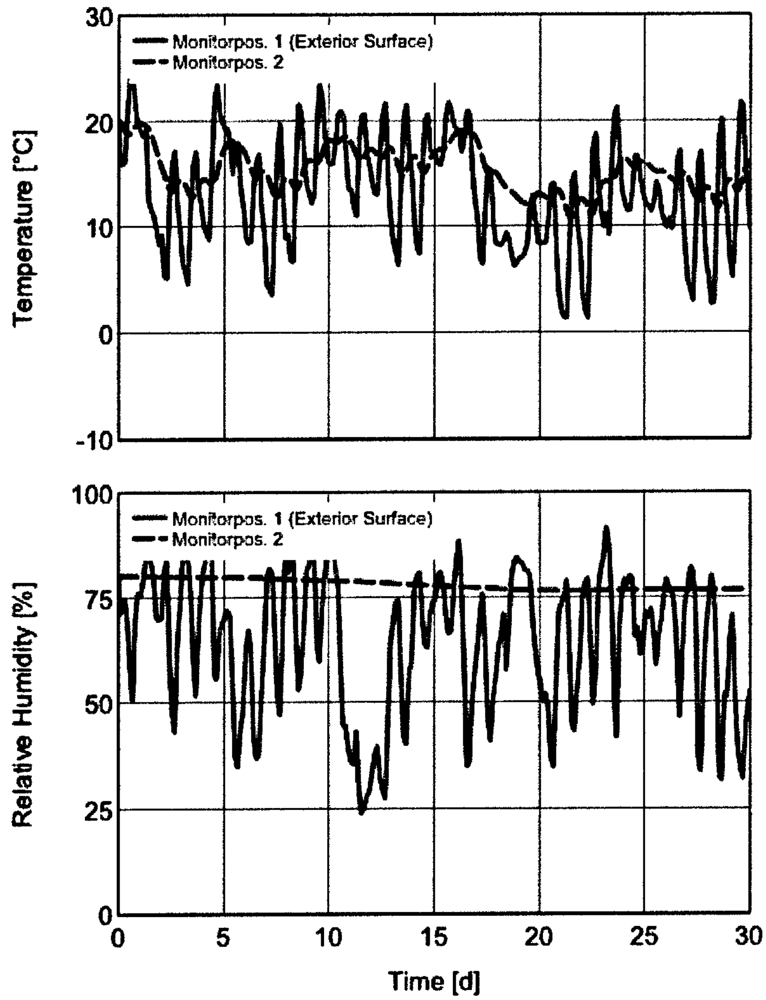

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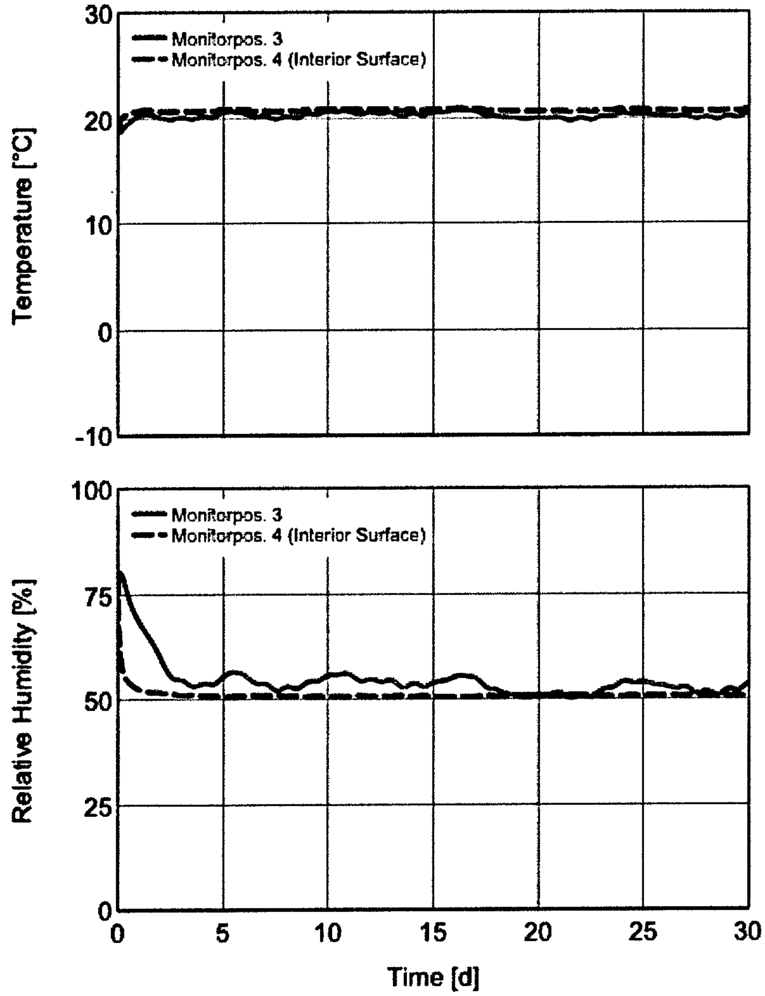

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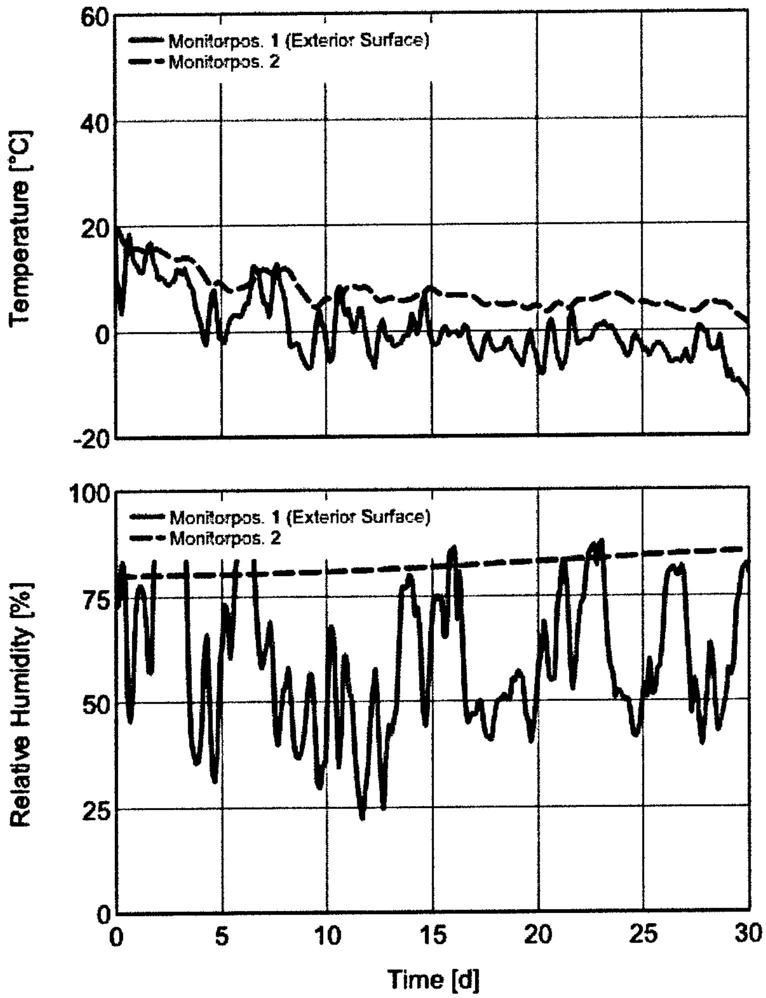

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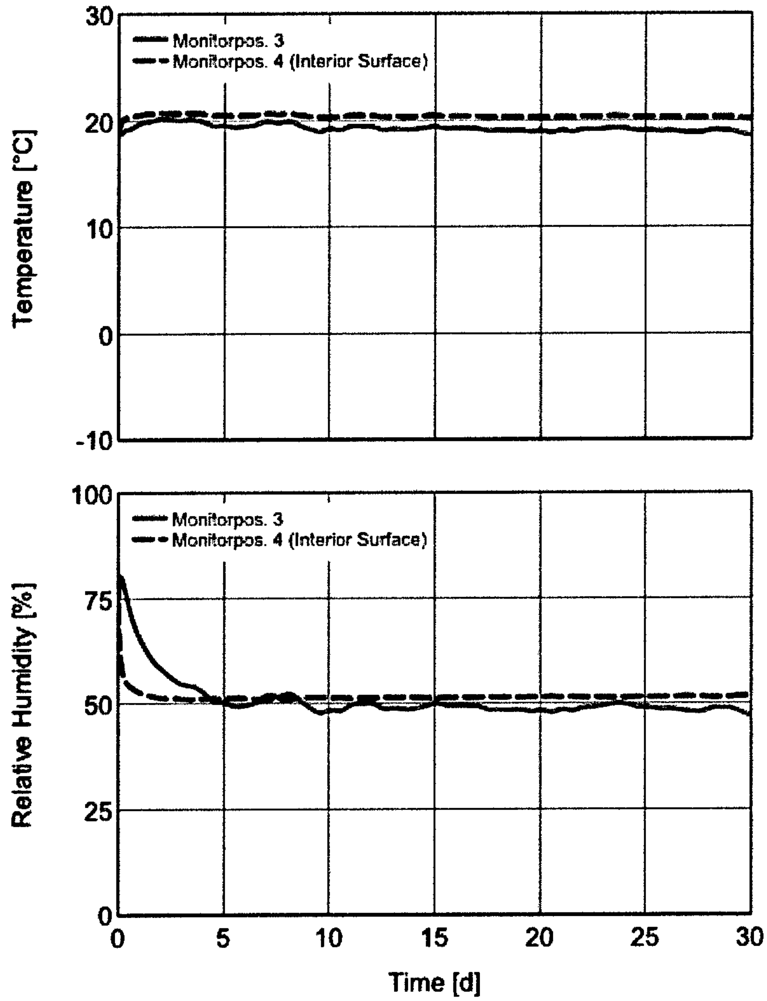
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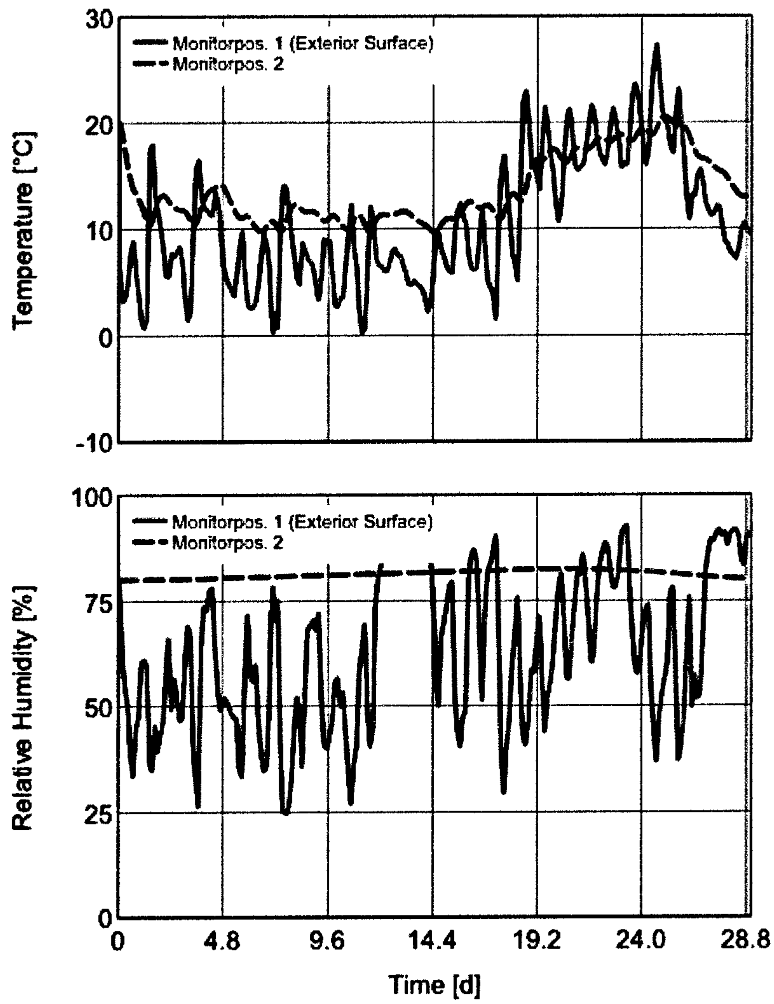

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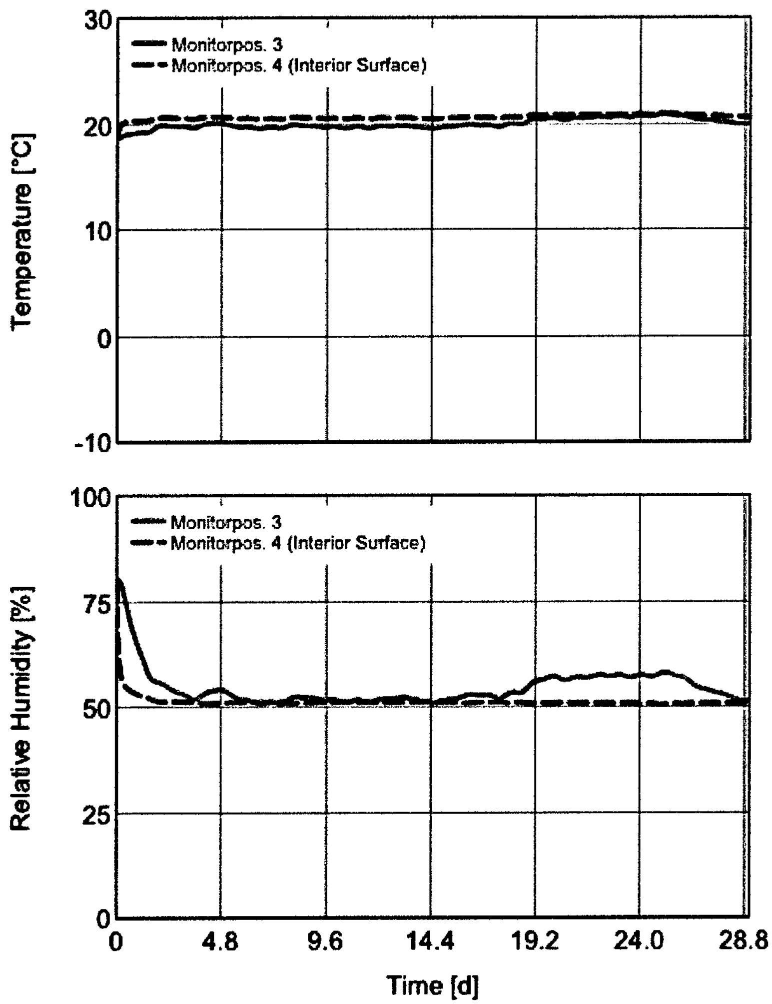
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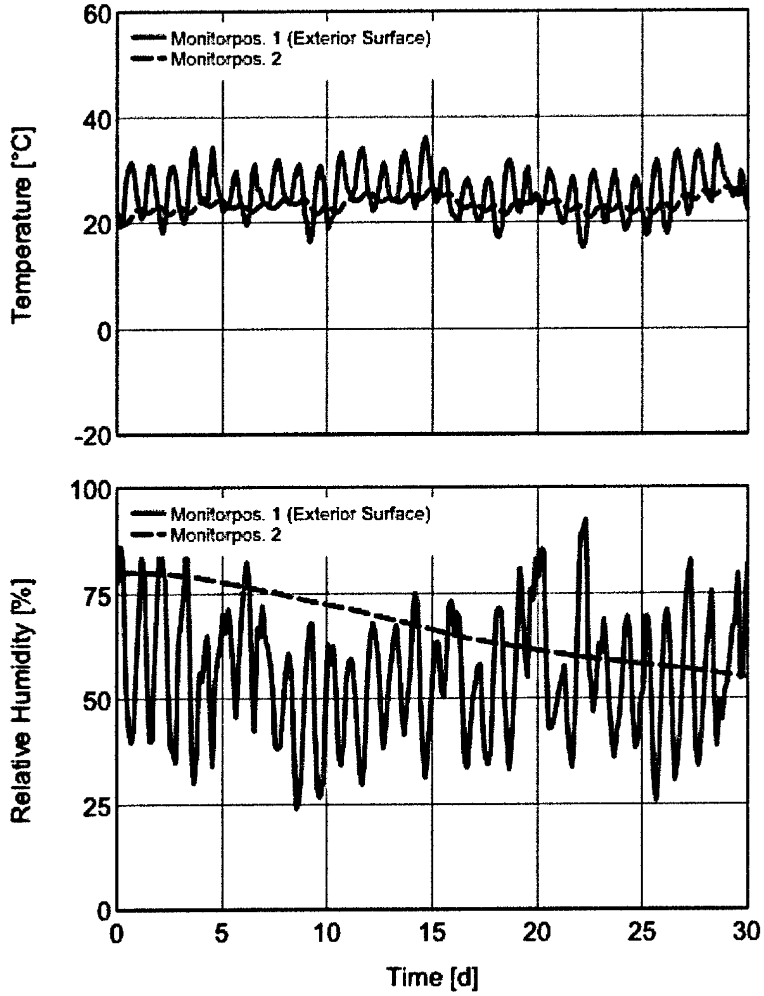
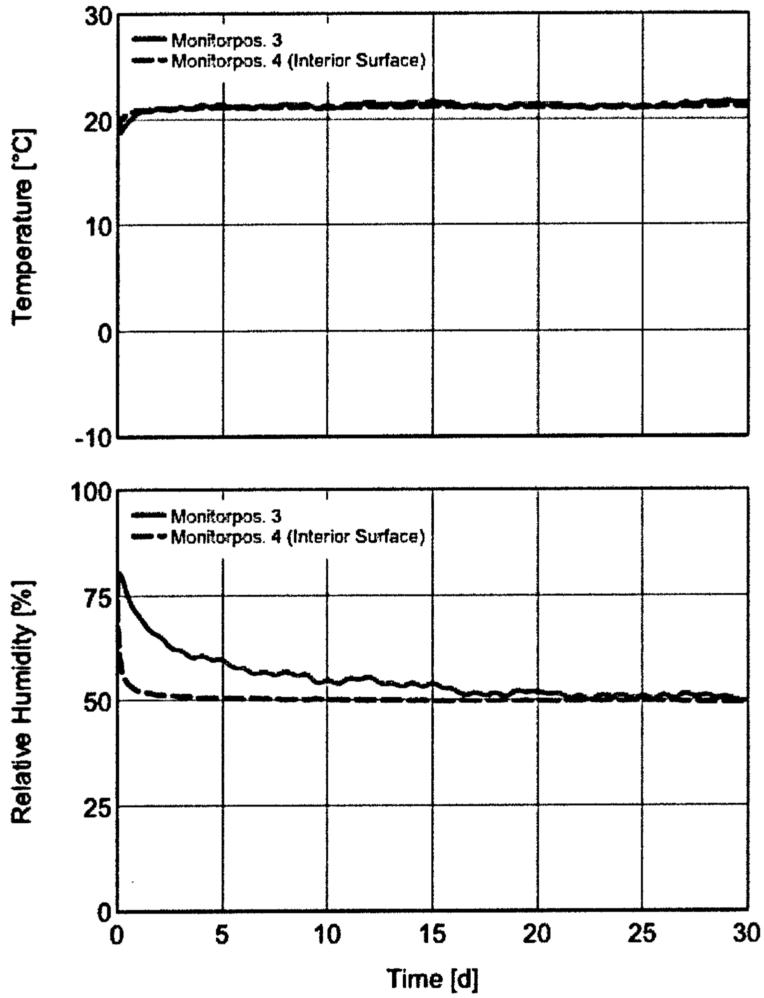


Project: Project and Report / Case 2: Spruce Siding Model - 2-VB-R-7-AC (New Orleans VB Location)



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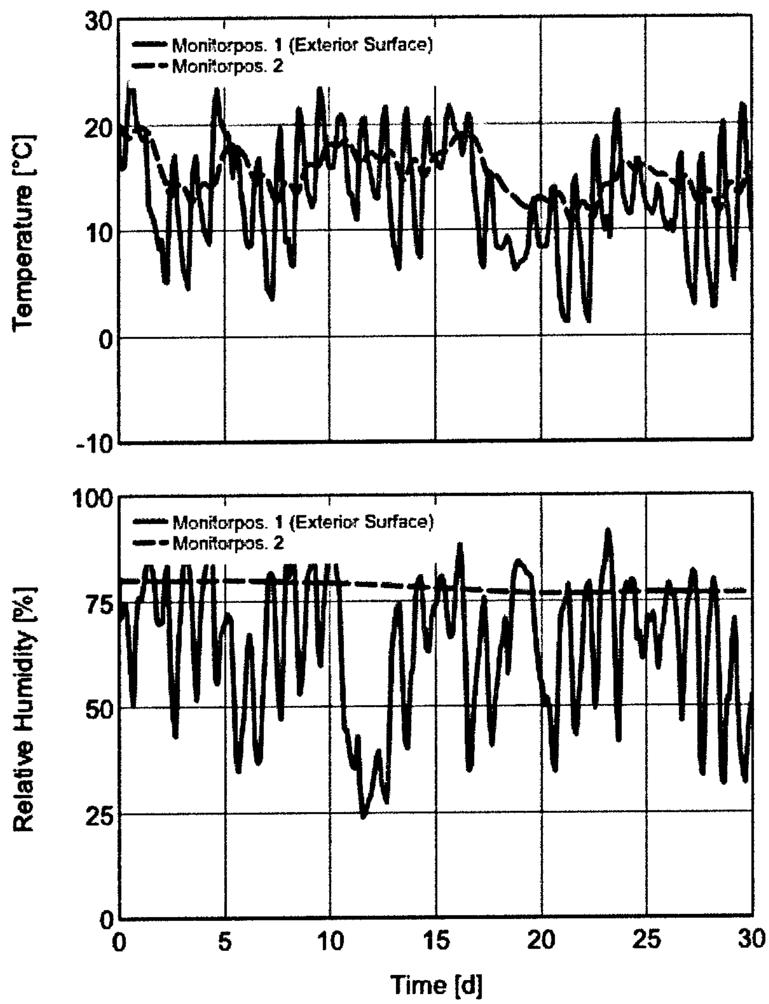

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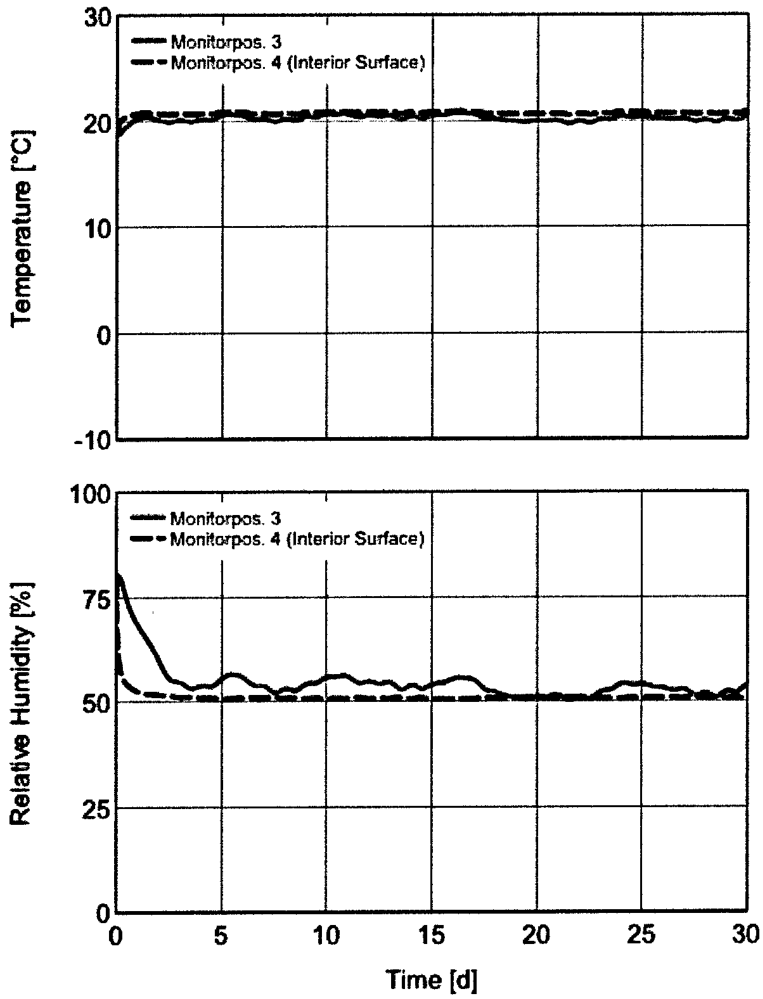
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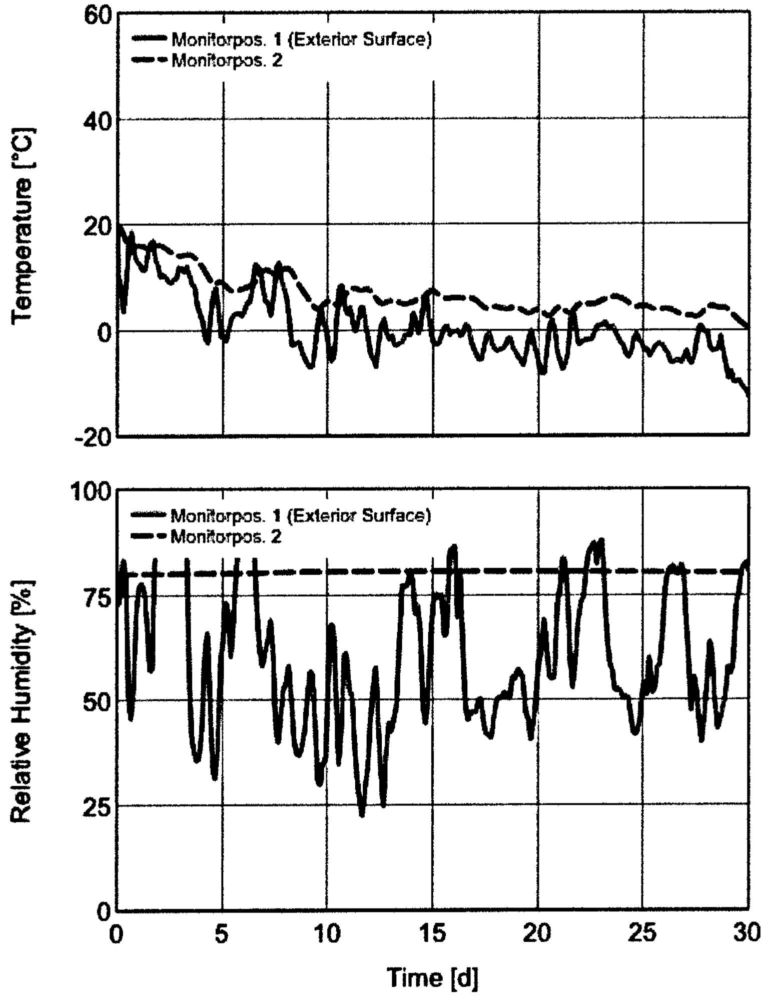

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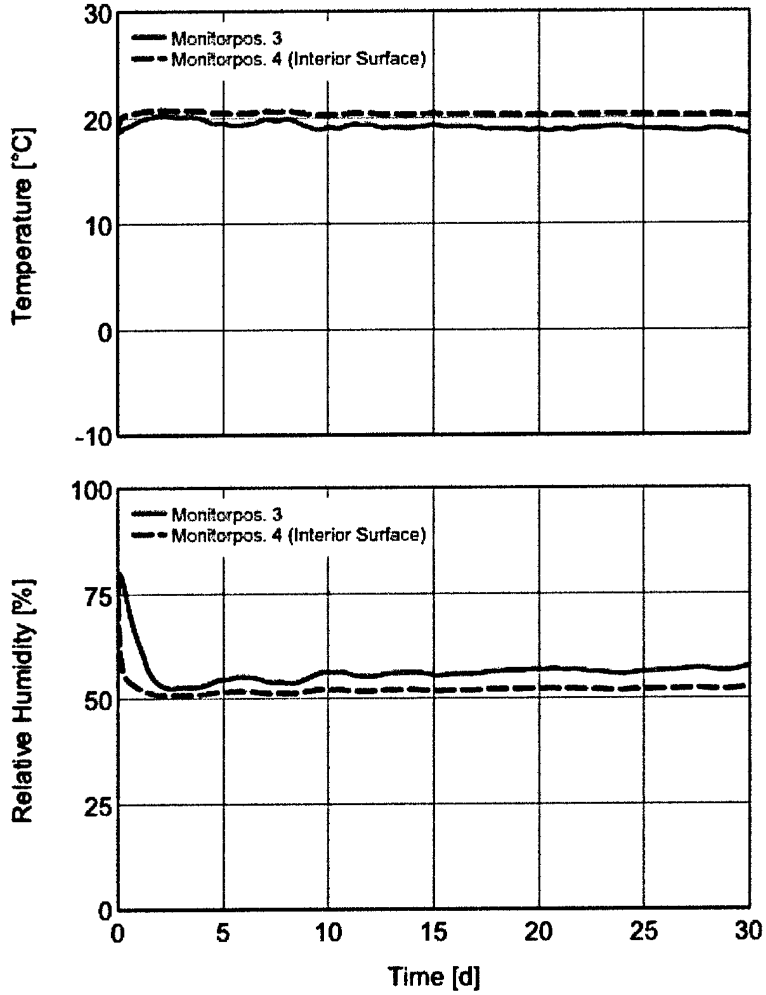
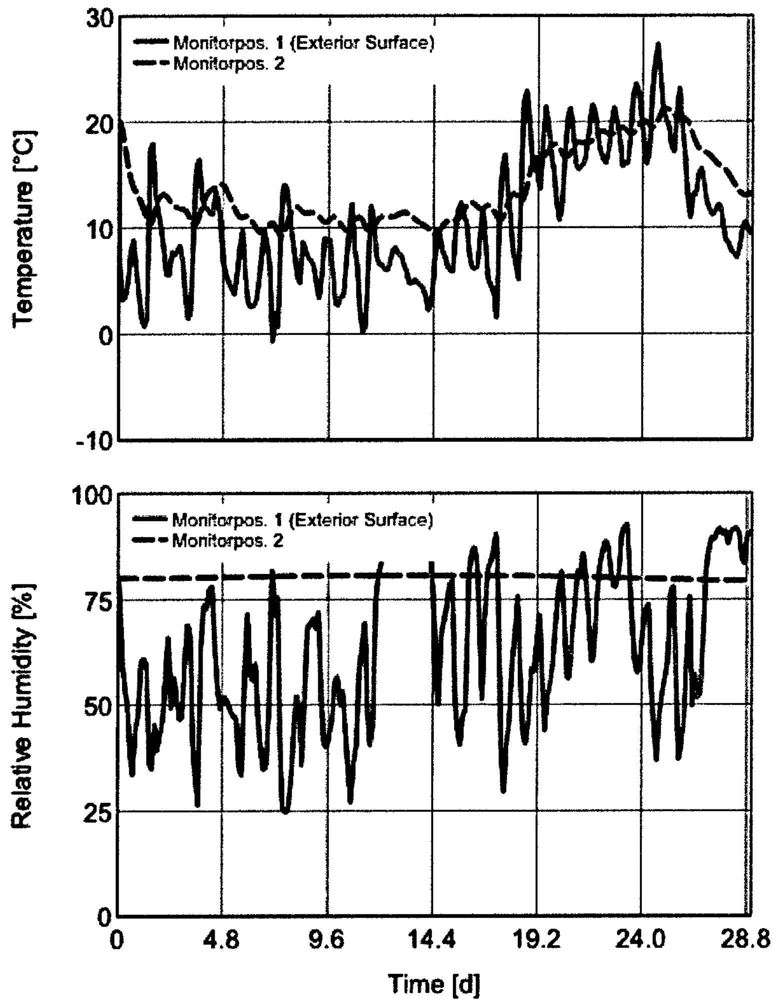


Project: Project and Report / Case 2: Spruce Siding Model - 2-VB-R-1-AC (Minneapolis VB Location)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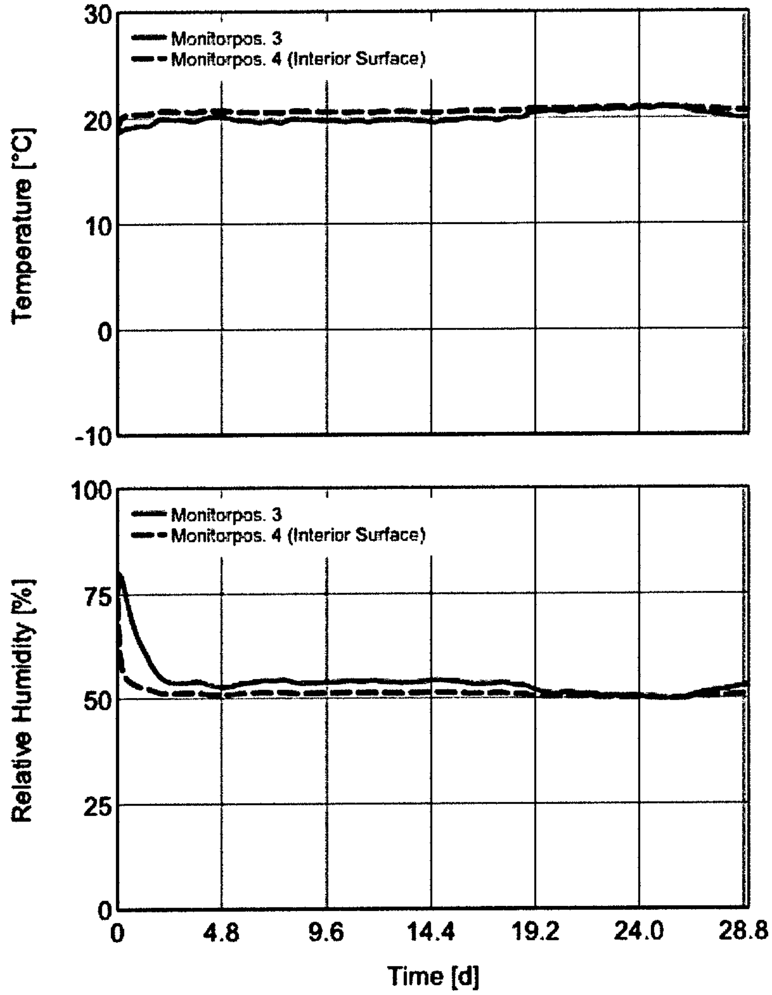
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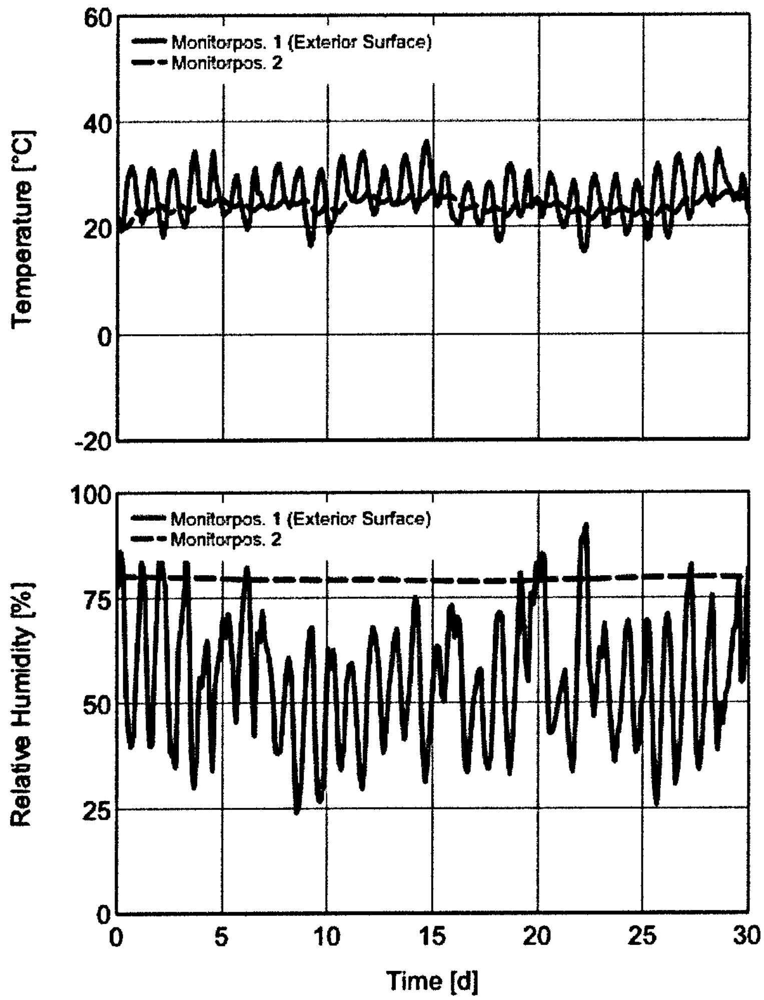

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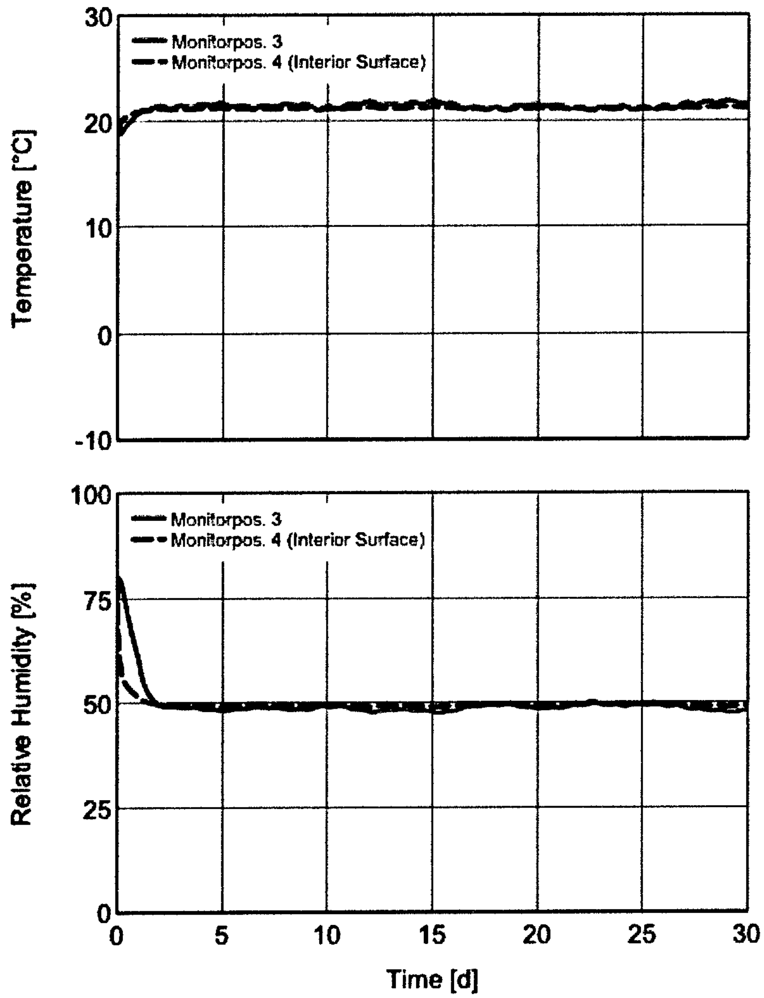

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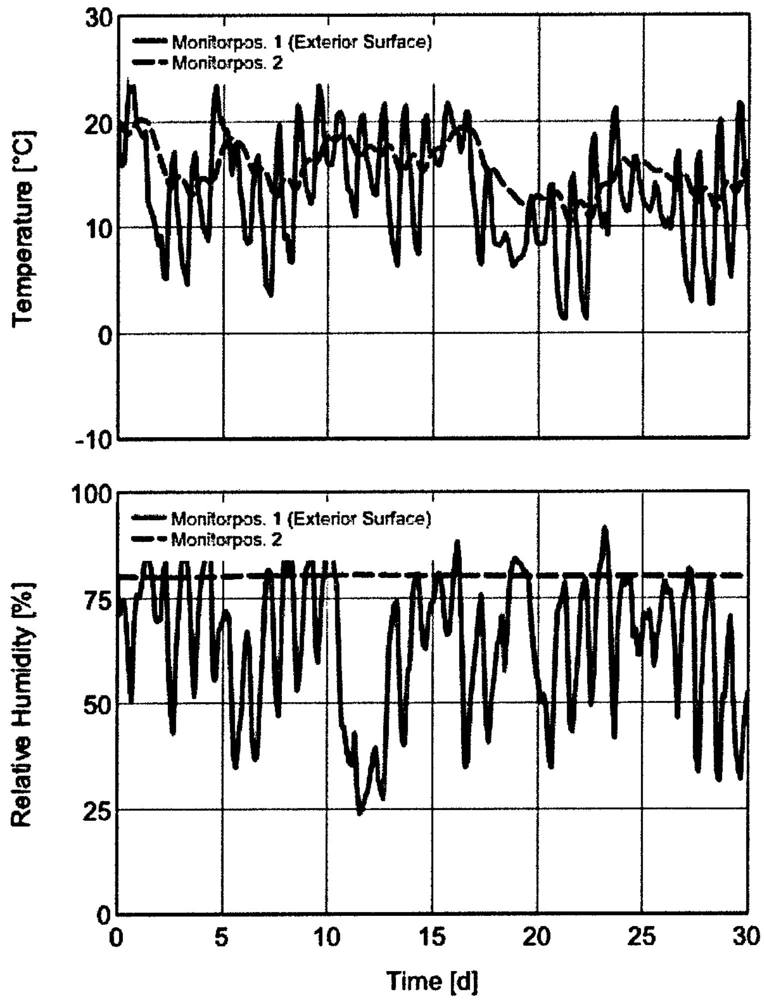
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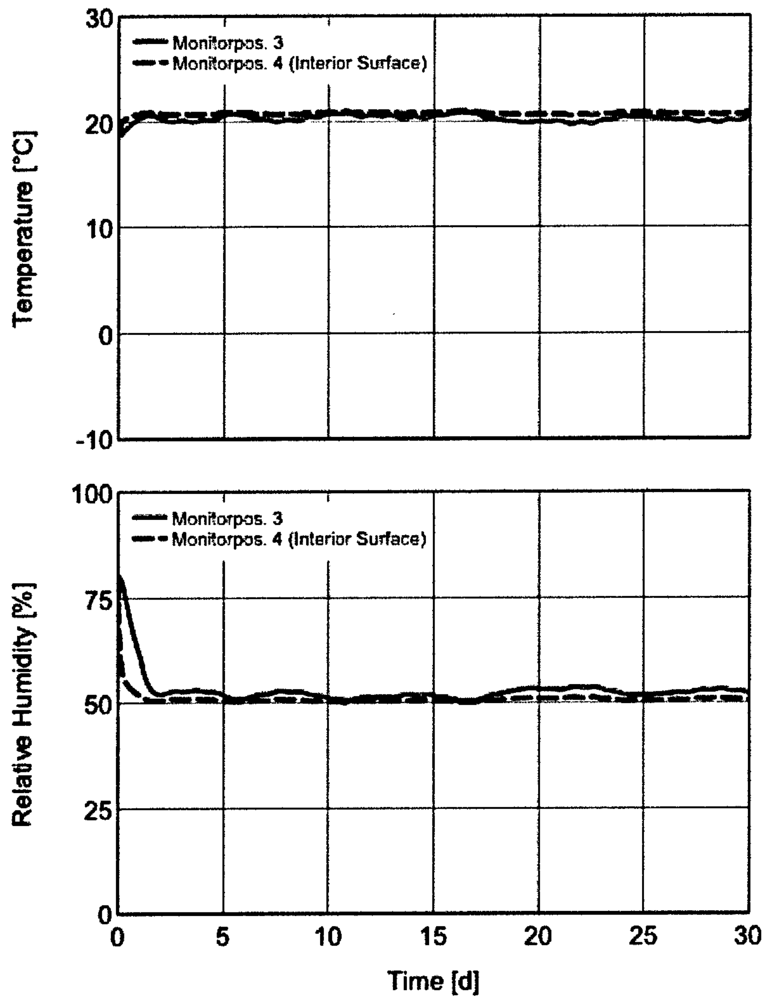
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